# REENGINEERING AND FAST MANUFACTURING FOR IMPACT-INDUCED FATIGUE AND FRACTURE PROBLEMS IN AGING AIRCRAFTS

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## Final Report

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In this research, a systematic reverse engineering, re-engineering, and fast manufacturing (RRF) process has been developed and validated. Commercial off-the-shelf (COTS) software tools and equipment that support the RRF process have been identified, evaluated, and tested. An integration framework has also been developed and employed to create an RRF testbed. This testbed constructed using COTS software and equipment supports three major engineering tasks: the reverse engineering that supports recovering of technical data from worn sample parts, re-engineering that alters design for better performance or lower cost, and fast prototyping that incorporates advanced manufacturing technologies to produce functional or physical prototype of the part in small quantity in a short turnaround time. A number of examples obtained from logistics centers have been employed to illustrate and demonstrate the capabilities established in the RRF testbed. This testbed allows a geographically distributed team to work on a design task both synchronously and asynchronously. This testbed was presented and demonstrated to OC-ALC personnel on November 30, 2005, and received very positive feedback and excellent suggestions.

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# ABSTRACT

This report summarizes results of the AFRL-sponsored research project entitled: Reengineering and Fast Manufacturing for Impact-Induced Fatigue and Fracture Problems in Aging Aircrafts. The performance period was between June 15, 2002 and December 14, 2005. The research work was conducted at The University of Oklahoma (OU) Norman Campus with technical support received from OC-ALC and aerospace contractors.

The primary objective of the project is to develop a systematic, accurate, and efficient re-engineering and prototyping technology for fatigue and fracture of mechanical parts and subsystems, especially due to impact loads, for both military and industrial applications. The goals are to demonstrate such a technology, to support Oklahoma City Air Logistics Center (OC-ALC) to establish similar integrated system in the near future, and to assist OC-ALC to gradually build up expertise to adequately tackle the fatigue and fracture problems. Ultimately, the system developed in the proposed research will support OC-ALC engineers to re-engineer and manufacture quality parts and subsystems that enhance reliability of the aging fleets, therefore, overcoming the new challenge and successfully accomplishing OC-ALC's missions.

In this research, a systematic reverse engineering, re-engineering, and fast manufacturing (RRF) process has been developed and validated. Commercial off-the-shelf (COTS) software tools and equipment that support the RRF process have been identified, evaluated, and tested. An integration framework has also been developed and employed to create an RRF testbed. This testbed constructed using COTS software and equipment supports three major engineering tasks: the reverse engineering that supports recovering of technical data from worn sample parts, re-engineering that alters design for better performance or lower cost, and fast prototyping that incorporates advanced manufacturing technologies to produce functional or physical prototype of the part in small quantity in a short turnaround time. A number of examples obtained from logistics centers have been employed to illustrate and demonstrate the capabilities established in the RRF testbed. This testbed allows a geographically distributed team to work on a design task both synchronously and asynchronously. This testbed was presented and demonstrated to OC-ALC personnel on November 30, 2005, and received very positive feedback and excellent suggestions. A contract vehicle is being established between OU and OC-ALC to channel reverse engineering assignments more efficiently to OU, following suggestion of OC-ALC personnel. Once the contract vehicle is established, the research team at OU will be able to work with engineers and managers at OC-ALC simultaneously on specific tasks using the testbed facilities. The testbed and contract vehicle being established are important steps for realizing goals outlined in the near future.

This report will not only summarize the research tasks accomplished but will also focus on presenting engineering capabilities established in the testbed. Some capabilities developed extraneous to the project have been integrated and included in the testbed. They will be briefly introduced in this report in order to provide a complete picture of the testbed.

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# 1. INTRODUCTION

Many weapon systems in the U.S. Armed Services and around the world were developed forty, even fifty years ago. After the Cold War ended, the U.S. Department of Defense (DoD) decided to extend the service life of existing weapon systems for a prolonged period, rather than spending billions of dollars for development of new systems. Logistics centers face a major challenge in maintaining weapon systems originally designed half a century ago—systems that are approaching, or have already reached the end of their intended service lives. The challenge stems from the premise that the existing systems designed using outdated technology simply cannot keep the systems in service consistently and reliably. In addition, the original technical data packages, including engineering drawings, of the failed parts in weapon systems are either incomplete or completely missing [1]. The situation creates serious problems in acquiring parts externally as well as for conducting in-house manufacturing.

For some time, logistics centers have adopted various reverse engineering approaches that replicate original parts from physical samples. These approaches have provided some success in supporting logistics centers to accomplish its MRO (maintenance, repair, and overhaul) missions for the past two decades. Recently, some logistics centers, such as OC-ALC (Oklahoma City Air Logistics Center), have attempted to accelerate the process by implementing an aggression of modern scanning devices with surface construction technology [2]. However, the discrete point clouds created using modern scanning devices are often in millions, which usually require a great deal of human efforts to convert them into useful forms. Furthermore, the accuracy of the restored part geometry often is not characterized quantitatively due to lack of adequate tools.

Among many engineering problems encountered in logistics centers, the problem of fatigue and fracture, often present in critical impact load-carrying subsystems, such as landing gears, suspension components, etc., is the most technically challenging task. Especially, mechanical failures and safety hazards caused by fatigue and fracture problems often ground the weapon systems. In order to address the fatigue and fracture issues, excellent experimental facilities and engineering expertise have been established in some logistics centers to conduct fatigue and fracture tests. However, no computational techniques and design methods have been employed to re-engineer and improve reliability of the failed components. Even though, most of the parts function well, they were designed mostly based on experience and engineering intuition. Some of the parts were over-designed, and could be optimized to reduce weight and material consumption.

In manufacturing, some of the technology and facilities initially employed are out-of-date, and many vendors have discontinued their supplies to support logistics centers. In addition, to maintain fleets of small quantities, for example, Air Force AWACS (or E-3), only small quantity of parts are usually acquired by the logistics centers. This severely narrows the options of viable manufacturing methods and often leads to a no-bid situation after a prolonged acquisition process.

With such a formidable challenge on the horizon—extending the service lives of aging systems—advanced computer-based design and manufacturing technology, unavailable half a century ago, provides logistics centers a great opportunity to confront and overcome the challenge. Products and processes can be re-engineered for more durable and reliable alternatives, with faster and more cost-effective manufacturing options. For example, the E-3 torque tubes shown in Figure 1 were re-engineered for both reliability and manufacturing process [3]. Sample torque tubes were first measured for critical geometric dimensions using coordinate measurement machine (CMM) and FaroArm. The measurement data were employed for constructing parametric solid models manually using a CAD system, in this case, *Pro/ENGINEER* [4]. Once the parametric solid model was available, the product and process re-engineering activities were conducted concurrently. In re-engineering the tubes, strength analyses were conducted for both magnesium and aluminum solid models. In order to reduce the weight of the aluminum tubes while maintaining their strength, the tube geometry was changed using shape optimization technique. A sample aluminum tube was machined and delivered to OC-ALC for material strength test. The aluminum tubes were both stronger and more corrosion-resistant than the magnesium tubes in service. More importantly, the cost of

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the tubes was reduced by more than 50% and there was a tenfold decrease in manufacturing lead-time. The key step that allowed product and process re-engineering was construction of parametric solid models. With parametric solid models, advanced design and manufacturing technologies can be readily employed for creating durable and economical replacements. In addition, a well-organized process with necessary tool set in place will make the RRF process more systematic and effective. The success and lessons learned from the torque tube examples prompt the idea of developing an RRF testbed.
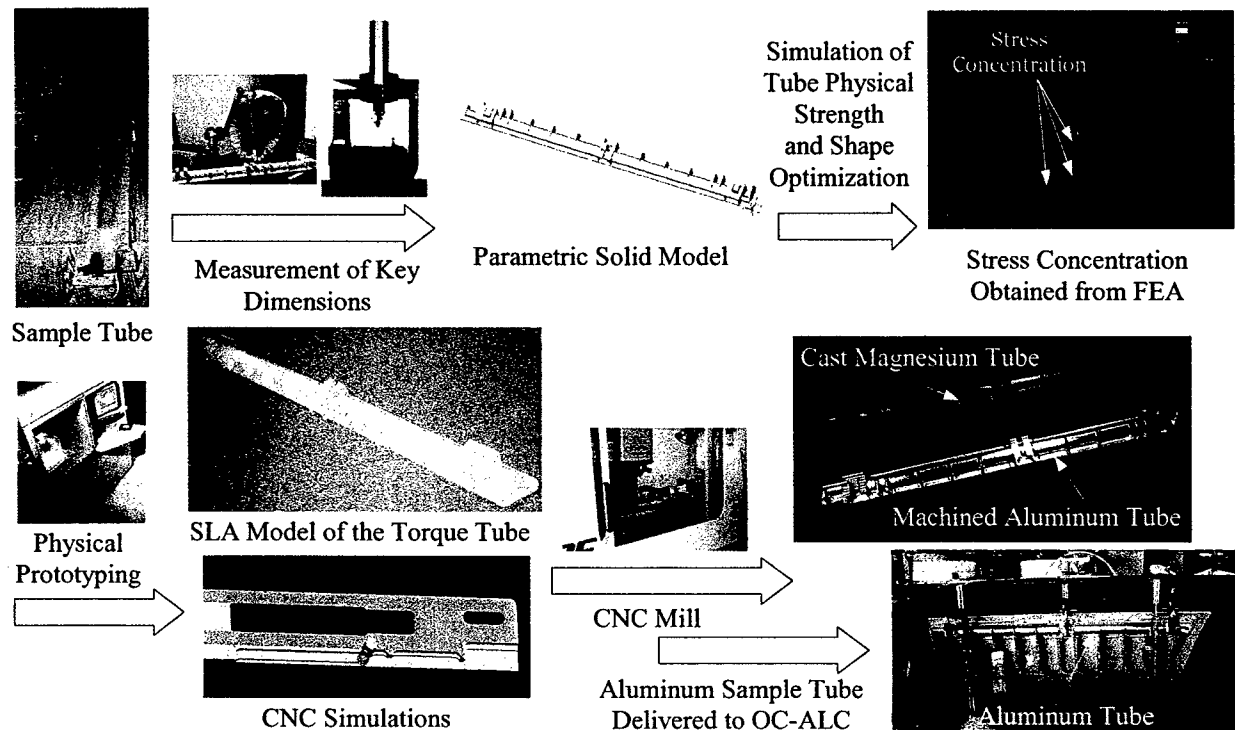


Figure 1  Reverse engineering, reengineering, and manufacturing of AWACS torque tubes

The objective of this project is to develop a systematic, accurate and efficient re-engineering and prototyping technology for fatigue and fracture of mechanical parts and subsystems, especially due to impact loads, for both military and industrial applications. The goals are to demonstrate such a technology, to support OC-ALC to establish similar integrated system in the near future, and to assist OC-ALC to gradually build up expertise to adequately tackle the fatigue and fracture problems. Ultimately, the system developed in the proposed research will support OC-ALC engineers to re-engineer and manufacture quality parts and subsystems that enhance reliability of the aging fleets, thereby overcoming the new challenge and successfully accomplishing OC-ALC's missions.

This report will not only summarize the research tasks accomplished but will also focus on presenting engineering capabilities established in the testbed. The RRF process and technical capabilities, including those developed outside of the project, are presented in Section 2. Integration capabilities are summarized in Section 3. In Section 4 the RRF testbed and testbed demonstration for OC-ALC personnel are reported. A brief summary is given in Section 5. Documents related to the testbed presentation and demonstration are summarized in Appendix A. A publication list is given in Appendix B and a list of reports and model files contained in the attached CD is given in Appendix C.

## 2. TECHNICAL APPROACHES

### 2.1 The Overall Process

The proposed RRF process, as illustrated in Figure 2, supports reverse engineering, reengineering, and fast prototyping. The reverse engineering aims at not only reconstructing solid models from physical sample parts, but more importantly, constructing parametric solid models with geometric features and dimensions. Usually, if reengineering is not in consideration, the NURB (Non-Uniform Rational B-spline) [5] surface models are sufficient for reverse engineering. However, in order to support reengineering, geometric features embedded in the NURB surface model must be recognized and properly parameterized.
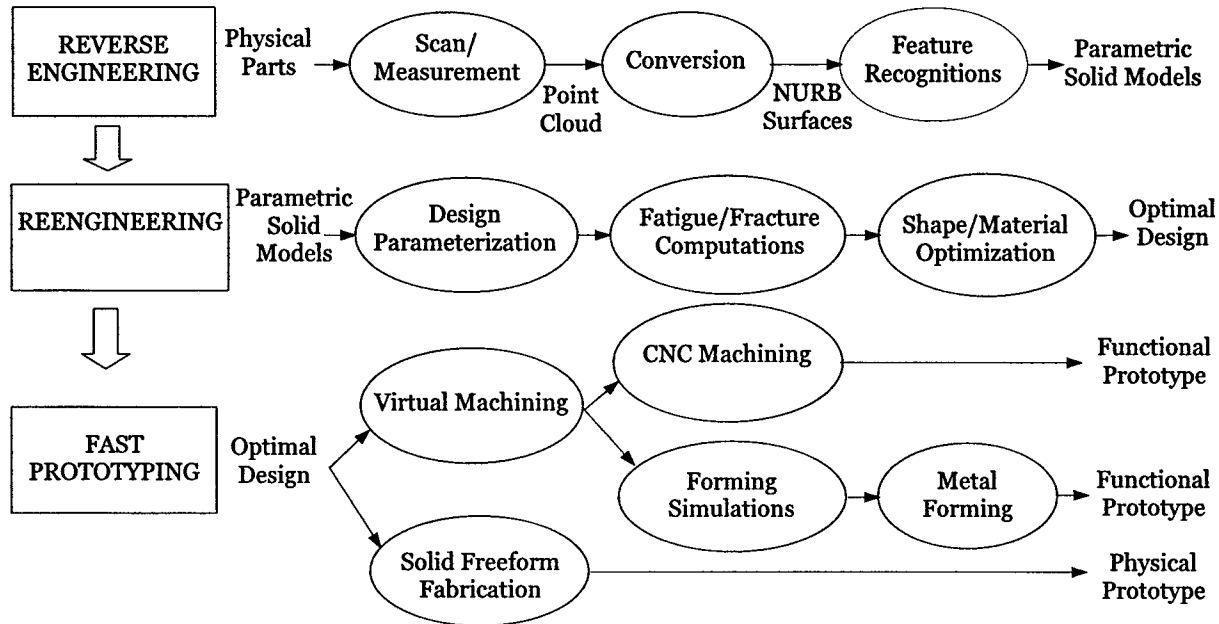


Figure 2 The proposed RRF process

The reengineering phase focuses on incorporating fatigue and fracture computations as well as shape optimization for optimal or near-optimal component designs. Computer modeling and simulation tools, such as multibody dynamic simulations, finite element analysis (FEA), and fatigue and fracture prediction techniques have been employed to simulate the fatigue and fracture behavior of the failed parts. Based on the simulation results, material and part geometry can be optimized for required performance with minimum cost (or minimum part weight in most cases) as the objective function.

In the fast prototyping, the solid freeform fabrication (SFF) technology (also called Rapid Prototyping) [6] is employed to fabricate physical prototypes of the re-engineered parts for design verification. At the same time, virtual machining and metal forming simulations will support manufacturing process planning and simulation before fabricating the functional prototype or embarking on parts manufacturing. Once the virtual machining is completed, machining codes can be generated to drive the CNC machines to cut functional parts.

An integration framework is developed using *Windchill* of Parametric Technology Co. [7] to embrace the tools and technology involved, support design collaboration, and facilitate information sharing and project management. More details are explained in the following sections.

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## 2.2    Reverse Engineering

One of the major steps in reverse engineering is recovering part geometry from the physical sample. The geometry recovering process consists of three steps, the scanning or measurement to capture the part geometry in discrete points, converting points into useful surface forms, and recognizing geometric features embedded in the surfaces and converted them into parametric solid models.

*Scanning Devices*

There are many different kinds of scanning or measurement devices. Basically, they belong to contact or non-contact category. The probe at the tip of a contact measurement device, such as a coordinate measurement machine (CMM), must contact the part surface to record the location of the surface points. Both portable and fixed devices are available to meet different needs. The non-contact type devices usually employ laser beam or X-ray for scanning or measurement. Note that the non-contact devices, including optical, laser, CT (Computer Tomography), MRI (Magnetic Resonance Imaging), etc., usually work very well with freeform surfaces, e.g., biological parts. Mechanical parts may contain regular entities, such as circular holes, or sharp edges, which sometimes present difficulty for the scanning devices. In general the non-contact devices generate thousands to millions of points in minutes and provide high levels of accuracy in support of engineering tasks [8].

The scanned discrete points are called *point clouds*. In order to support engineering tasks, point clouds must be further processed to a more useful and manageable form. Very often, a point cloud is first fitted with a triangular mesh, from which curves and small patches are constructed. The patches are then converted into a surface model, usually in a NURB format. The mathematical conciseness of the NURB representation greatly simplifies data management and numerical computations, thereby allowing excellent geometric visualization and relatively good manufacturing support. However, the surface models are not equipped for support of engineering designs because they are not parametric. Without parameterization, they cannot be changed or documented in engineering drawings with proper dimensions. In addition, the NURB surface representation hinders geometric feature recognition due to the fact that NURB patches (small surface pieces) tend to capture intrinsic details of the unintended geometric features (such as welds) and the NURB patches are not mathematically compatible with regular surface representations found in CAD, such as cylindrical surfaces, revolved surfaces, etc.

*Reverse Engineering Process*

The reverse engineering of this research focuses on developing a process for creating parametric solid models from digital point clouds using COTS software tools. The modeling approach employs both surface construction and feature recognition techniques. These parametric solid models are critically important for logistics support, primarily re-engineering failed parts found in aging systems. An ideal scenario that requires minimal effort from users, while still provides accurate enough parametric solid models with design intents recovered is proposed (Figure 3) [9]. COTS tools, including *Imageware* [10], *ICEM* [11], *Paraform* [12], *GeoMagic* [13], *CATIA* [14], and *FeatureWorks* [15] have been investigated and found insufficient in completely realizing the ideal scenario. Essentially, no contemporary COTS tool was able to automatically convert point clouds into complete surface models. Extensive manual work was often involved. Furthermore, when feature recognition was performed in a batch mode using *FeatureWorks*, The program either failed to recognize geometric features or they were recognized without proper design intents [9]. Hence, alternative process and approach must be searched for effectively using the COTS software tools.

*Test Example and Process*

A used B-52 airplane tubing example shown in Figure 3 was employed to support the study. Note that the tubing example represents a common yet geometrically sophisticated application due to its exterior and interior geometry as well as the curvatures present in individual branches.
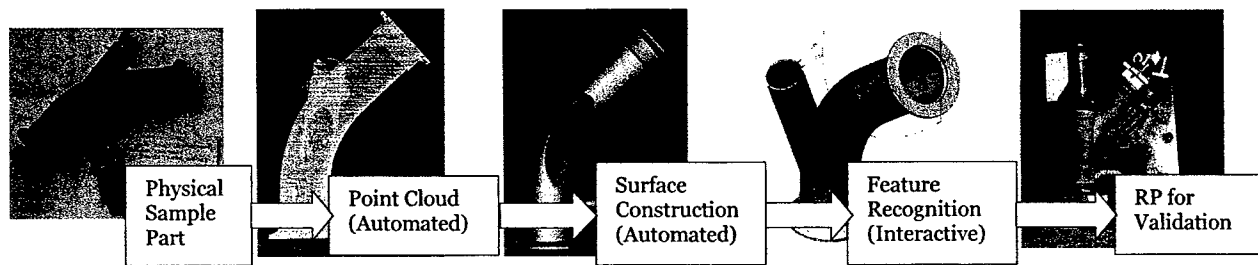
Figure 3  Overview of feature capturing process

The sample part was first scanned using an industrial CT scanner with a 0.3 mm resolution, which captured both interior and exterior geometry of the part, producing a dense cloud of 486,107 uniformly distributed points, as shown in Figure 4a. *Imageware* was used to separate the full cloud into several feature clouds (4b), representing surfaces of the five solid components; i.e., two flanges, main tube (inner and outer), large branch (inner and outer), and small branch (inner and outer). Note that the two fittings were not included since they are standard off-the-shelf parts. To insure consistency, the same set of separated feature clouds was used throughout the study. The feature clouds were then used to construct a closed surface model (4c and 4d). The surface model was then exported for feature recognition, (ideally) resulting in a parametric solid model (4e). Finally, the completed model was brought back to either *CATIA* or *Imageware* where a cloud-to-surface error analysis measured normal distances from the original data points to the constructed surfaces (4f).
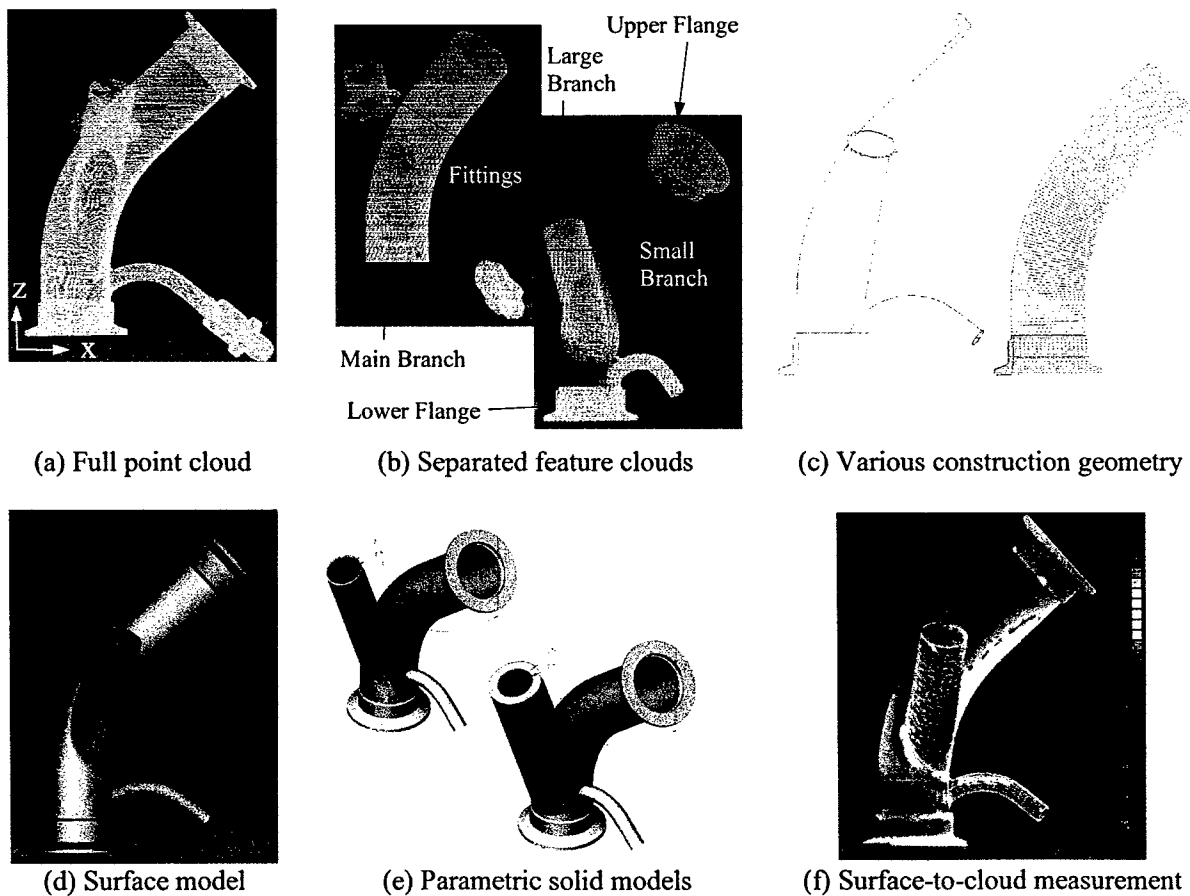


(a) Full point cloud

(b) Separated feature clouds

(c) Various construction geometry



(d) Surface model

(e) Parametric solid models

(f) Surface-to-cloud measurement

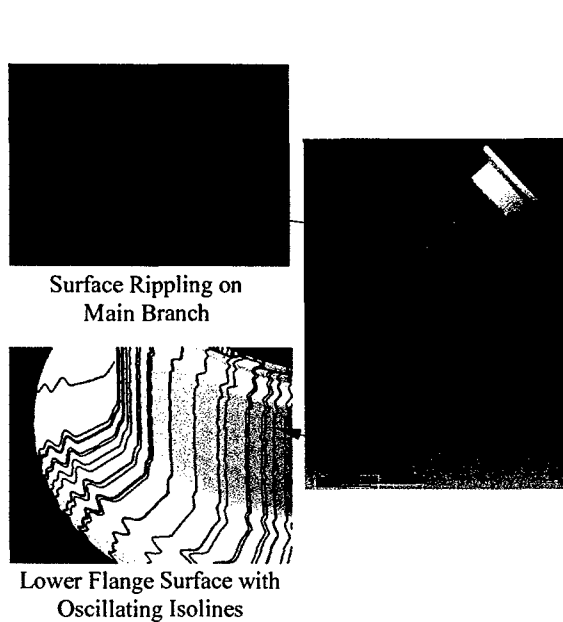Figure 4  Overview of the testing process

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Under the framework of the testing process shown in Figure 4, there are almost an infinite number of ways to construct surface and parametric solid models using the decomposed point clouds, i.e., from steps 4c to 4e. In this research, four representative approaches are devised, with consideration to geometric accuracy, manual labor, and computing resources. They are: (1) detail capturing (or exact model), (2) skeleton surface construction, (3) direct solid modeling (without feature recognition), and (4) component modeling.

In detail capturing (exact model) approach, the emphasis was placed on accuracy and as many points as possible were used to construct surface model. A triangular mesh was automatically generated for each component. A set of parallel planes along the scanning direction (Z-direction) with a 0.3 mm interval was created. The intersecting points of the planes and triangular mesh were used for curve construction. A total of 2,358 interpolation curves were constructed for the five components separately. These curves were then lofted to create a total of 92 surface patches. A common *scan-aligned* lofting option [14] was chosen to insure the complete capture of all the geometric details represented in the point cloud. Although this method clearly captured maximum detail, it was time and resource intensive. Other issues, such as poor surface quality due to capture of unnecessary details (like surface wear, etc.), gaps between components, and huge model size made this method infeasible. Also, surface oscillations, as shown in Figure 5a, due to high degree of interpolation curves would likely pose problems during feature recognition phase. As a result, no feature is recognized.
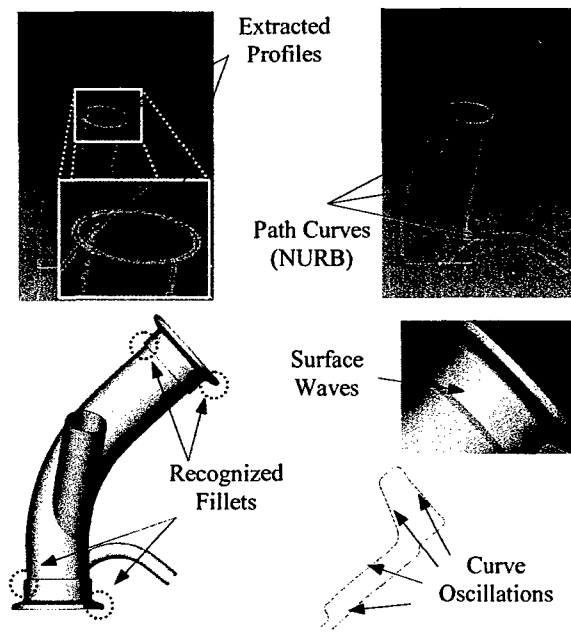
In skeleton surface modeling (Figure 5b), only the points representing section profiles were extracted from point clouds. Skeleton curves were then created using smooth approximation NURB curves. Using these skeleton curves, surfaces were created through extrusion, sweeping, or revolving operations. The surface model was exported into IGES (Initial Graphics Exchange Standards [16]) format and was imported into *SolidWorks* [17] for feature recognition using *FeatureWorks*. Even though the surface quality of the model created using this process was significantly improved, some slight oscillation waves due to the NURB construction were still present. *FeatureWorks* was able to identify only a few fillets, which showed that NURB surfaces constructed using the surface construction software tools were incompatible with the contemporary feature recognition capabilities.

In direct surface modeling, which slightly deviates from the testing process, the points defining section profiles were directly imported into CAD environment (in this case, *SolidWorks*) through IGES. Using the imported data as a tracing guide, completely new, fully parametric sketches were constructed. Simple test geometry was drawn over the point data. Hundreds of sample surfaces were created; their dimensions were tabulated and averaged to determine the final dimensions to be used for a particular feature. Finally, the sketches required for constructing the solid features were created and manually adjusted to fit the point data (Figure 5c). Because the initial feature sketches were based on averages taken over the respective components, it was difficult to guarantee accuracy over the entire part once the actual features are created. Consequently, the finished model would probably need adjustments to improve accuracy. However, since the process inherently results in a fully parametric model, the model can be fully adjusted to meet accuracy requirements.
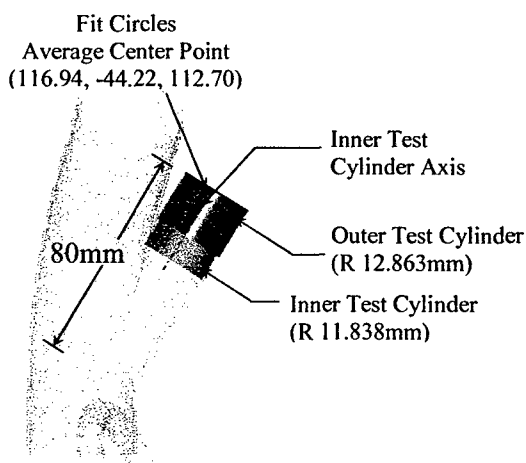
In the component modeling approach, section profile sizes and placements were pre-determined directly from the cloud data using ideas similar to those of the direct solid modeling. To avoid problems due to intersecting features, surface models of the five components were created separately, as shown in Figure 5d, and exported into IGES. The IGES models were separately imported into *SolidWorks*, where feature recognition was conducted individually using *FeatureWorks*, and was successful. These features can be merged later on to produce a complete parametric solid model. Further, features that are independent of each other can be merged or unmerged and their position in the feature tree can be altered. Although some adjustments were necessary to obtain accuracy similar to direct solid modeling, this method is particularly useful for more complex components.
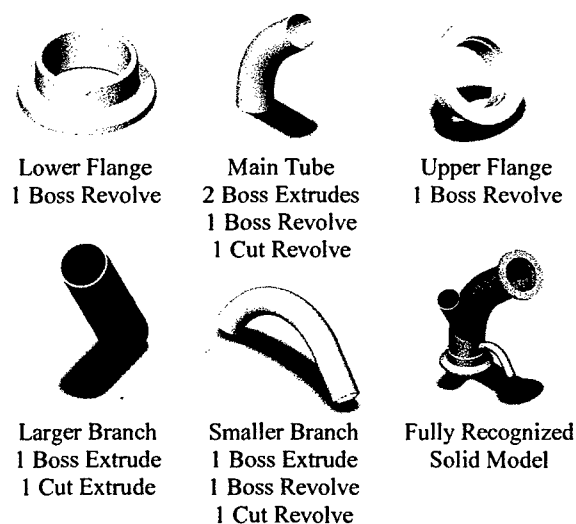
Surface Rippling on
Main Branch

Lower Flange Surface with
Oscillating Isolines

(a) Surface oscillation in detail surface model



Extracted
Profiles

Path Curves
(NURB)

Surface
Waves

Recognized
Fillets

Curve
Oscillations

(b) Illustration of skeleton surface modeling approach



Fit Circles
Average Center Point
(116.94, -44.22, 112.70)

Inner Test
Cylinder Axis

Outer Test Cylinder
(R 12.863mm)

Inner Test Cylinder
(R 11.838mm)

80mm

(c) Direct solid modeling



Lower Flange
1 Boss Revolve

Main Tube
2 Boss Extrudes
1 Boss Revolve
1 Cut Revolve

Upper Flange
1 Boss Revolve

Larger Branch
1 Boss Extrude
1 Cut Extrude

Smaller Branch
1 Boss Extrude
1 Boss Revolve
1 Cut Revolve

Fully Recognized
Solid Model

(d) Component surface modeling

Figure 5  Surface and solid models constructed using various methods

A physical sample of the tubing was fabricated through SLA-7000, an SFF machine from 3D Systems [18], using the solid model created by the component modeling approach. The physical sample shown in Figure 3 was then brought to Globe Engineering of Wichita, Kansas, who was able to successfully reproduce a replacement tubing part that would correctly assemble to the aircrafts. The sample was mounted on the production fixtures designed and manufactured by Globe Engineering (Figure 3). The sample fits well on the fixtures, and according to Globe Engineering's staff, the sample part would fit an actual aircraft.

*Observations*

As pointed out earlier, the ideal scenario could not be realized using contemporary COTS tools. The best possible way of constructing parametric solid models from point clouds using existing COTS tools was perhaps the direct solid modeling. The direct solid modeling approach allows designers to create parametric

solid models directly from point clouds, skipping time-consuming surface construction and not-quite-capable feature recognition steps. Furthermore, the parametric solid models can be easily modified and adjusted to minimize its deviation from the point cloud. The major drawback is that the engineer must be experienced with CAD tools and could end up spending a considerable amount of time for geometrically complicated applications.

Throughout the test, three major issues were identified. First, the surface construction has not been fully automated. All COTS tools demanded that users have significant geometric modeling knowledge, advanced computer skills, and lots of patience. Moreover, they all have steep learning curves and often required extensive training even for the most basic tasks. Even average applications could be labor intensive, because users must deal with points, curve segments, and many small surface patches, instead of simpler solid features commonly offered in CAD. Second, the existing feature recognition tools only recognized limited types of features in a very rigid way; that is, only one option among other possible feature forms was determined and given to the users. Third, the NURB surface models constructed were not suitable for feature recognition. The surface model consisted of a network of $G^1$ (slope continuous) NURB patches, which were often too irregular for feature recognition.

*Future Research*

A number of critical capabilities to be developed by both commercial and research sectors that are required for realizing the ideal modeling scenario were recommended [9]. Among which, Hoppe-Eck's algorithms [19] were found promising in fully automating the surface construction process. Venkataraman's algorithms [20] for feature recognition must be further improved to support more feature types as well as engineers' effort to recover design intents interactively. Furthermore, the incompatibility of NURB surfaces generated from surface construction software and the regular CAD-like surfaces, such as extruded cylindrical surfaces, must be resolved in order to support the ideal scenario. More details have been included in [9].

## 2.3   Reengineering

While re-engineering old parts, it is often necessary to modify the design or to optimize existing design in terms of performance, material, or total cost. The designers must ascertain that the new or modified design is capable of withstanding working loads, has a desired service life, is manufacturable, and is cost-effective. In this research, three major capabilities have been developed and incorporated to support re-engineering structural components in aging systems. They are topology and shape optimizations, shape optimization for minimizing cost, and fatigue and fracture prediction coupled with multi-body dynamic simulations.

*Topology and Shape Optimizations*

Topology optimization has drawn significant attention in recent development of structural optimization. This method has been proven very effective in determining the initial geometric shape for structural designs. The main drawback of the method, however, is that the topology optimization always leads to a non-smooth structural geometry, while most of the engineering applications require a smooth geometric shape, especially for manufacturing. On the other hand, shape optimization starts with a smooth geometric model that can be manufactured much easier. However, the optimal shape is confined to the topology of the initial structural geometry. No additional holes can be created during the shape optimization process. The topology and shape optimizations have been integrated to support structural design effectively by taking advantage of both methods [21]. The integrated capability has been incorporated into the testbed for structural shape optimization.

A tracked vehicle roadarm example shown in Figure 6 demonstrates the integrated topology and structural shape optimization process [21]. After topology optimization, the boundary of the structure is not smooth. Therefore, B-spline curves and surfaces were used in the boundary smoothing process. Control points of the B-spline curves and surfaces were imported into CAD environment (in this case, *SolidWorks*) and geometry was reconstructed. The control points parameterized the boundary edges and surfaces of the reconstructed solid model and also served as design variables for shape optimization. Optimization was conducted next, and manufacturability of the optimized component was verified using virtual machining technique [22]. In addition to significant material saving, the optimized part also had improved structural performance and was manufacturable.
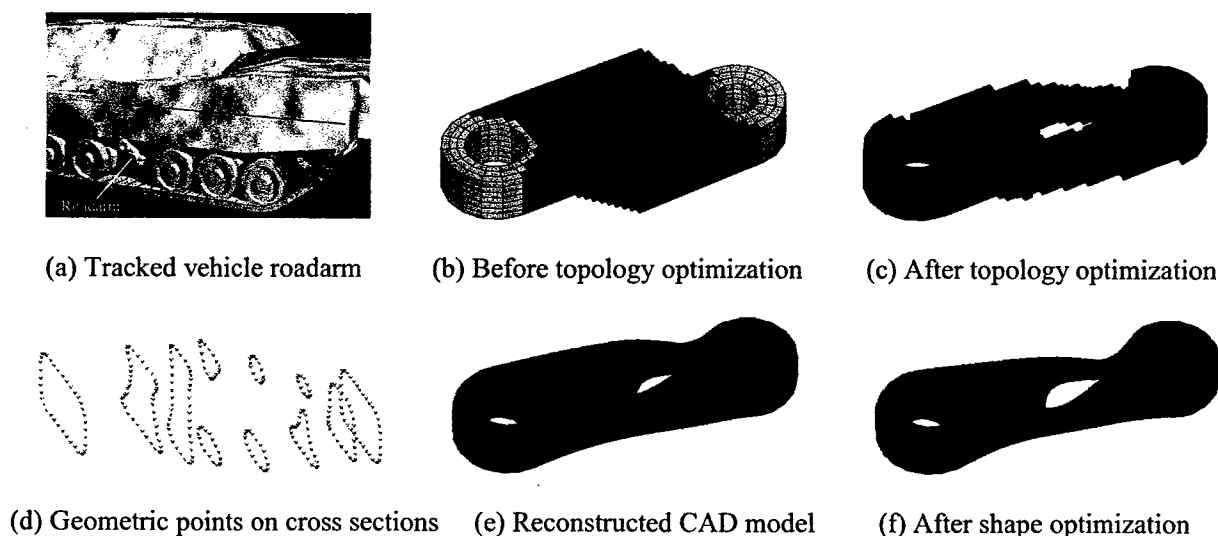


(a) Tracked vehicle roadarm      (b) Before topology optimization      (c) After topology optimization

(d) Geometric points on cross sections    (e) Reconstructed CAD model      (f) After shape optimization

Figure 6  Topology and shape optimization process applied to a tracked vehicle roadarm

*Shape Optimization for Minimizing Cost*

In this research, the integrated optimization process was taken one step ahead by integrating manufacturing into the optimization process. In particular, the work focused on incorporating manufacturing

cost into shape design optimization for heavy load carrying components. Material cost and machining cost together usually dominate the total cost for a machined part. The cost model included aforementioned costs as well as other costs, such as depreciation cost, cost of interest, operator overheads, etc. An optimization problem with manufacturing cost as an objective function and structural performance as constraints was successfully formulated as follows [23]:

Minimize:   $\phi(\mathbf{b})$

Subject to:   $\psi_i(\mathbf{b}) \leq \psi_i^u$   (1)

$b_j^\ell \leq b_j \leq b_j^u$

where $\phi(\mathbf{b})$ is the objective function; $\mathbf{b}$ is the vector of design variables captured in CAD solid models; $\psi_i(\mathbf{b})$ is the ith structural performance measure with its corresponding upper bound $\psi_i^u$; and $b_j^\ell$ and $b_j^u$ are the lower and upper bounds of the jth design variables, respectively. The objective function $\phi(\mathbf{b})$ is essentially the cost function for the component, defined as follows

$$\phi(\mathbf{b}) = C_{mat}\,\gamma\,V(\mathbf{b}) + C_{mac}\,\tau(\mathbf{b}) + C_t \qquad (2)$$

where the three terms represent material cost, machining cost, and tooling cost, respectively. In (2), $C_{mat}$ is the material cost rate ($/lb); $\gamma$ is the specific weight of the material; $V(\mathbf{b})$ is the volume of the component that depends on design; $C_{mac}$ is the machining cost rate ($/min); $\tau(\mathbf{b})$ is machining time that also depends on design; and $C_t$ is the tooling cost ($).

Equation 1 was solved using design optimization algorithm iteratively. For every design iteration, FEA was conducted to evaluate structural performance and virtual machining (VM) was employed to ascertain machinability and estimate machining time. Design sensitivity coefficients (gradients) of the objective and constraint functions were computed and supplied to the optimization algorithm. Based on the gradients, the algorithm determined design changes, which were used to update FEA and VM models. The process was repeated until specified convergence criterion was satisfied. Application programs developed to integrate commercially available CAD/CAM/FEA/Design optimization tools enabled implementation in a virtual environment, and facilitated automation. Therefore, this process requires minimal user-interaction once the initial models are defined and optimization process is started.

This integrated environment was applied to design an E-3 torque tube shown in Figure 7a, where holes are introduced to reduce weight. The objective function consisted of material and machining costs similar to (2). The length and depth of the seven holes (Figure 7b) were parameterized for design changes. The volume was computed by subtracting volume of holes from total volume of the torque tube. The maximum principal stresses at twelve critical locations were defined as the constraint functions with proper upper limits. A customized pocket milling sequence (Figure 7c) was defined in *Pro/MFG* [24] to simulate the machining process. It is apparent that changes in the hole sizes will vary the volume (hence the weight and cost) of the tube, may impact the structural integrity, and influence machining time of the tube. The optimization algorithm converged in four iterations. There was 2.4 % decrease in the cost. The weight of the torque tube was reduced by 6.1%. Machining time decreased by 10.6%. The optimization results are shown in Figure 7d. More details have been summarized in [23].
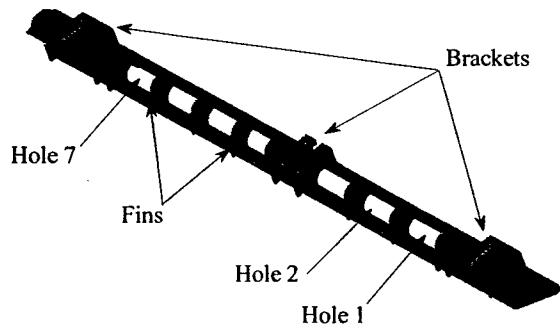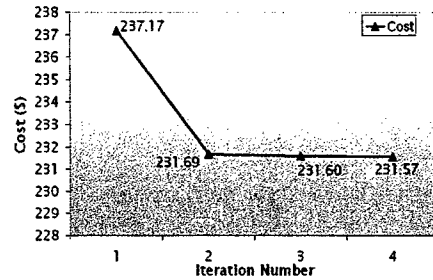
(a) Torque tube with holes
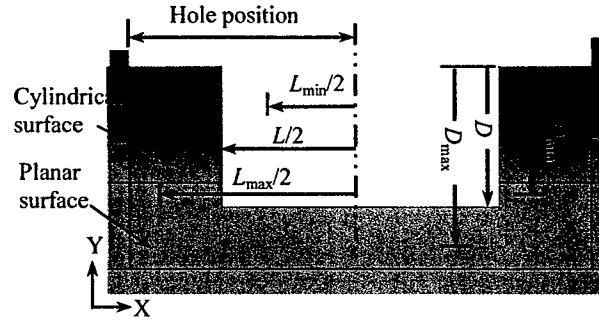


(b) Parameterization of holes
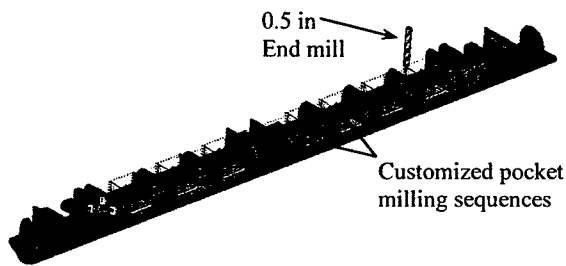


(c) Virtual machining simulation



(d) Design history for the objective function

Figure 7  Torque tube optimization

*Fatigue and Fracture Life Prediction*

As mentioned in Section 1, fatigue and fracture under the effect of dynamic loads are the most common causes of failure in mechanical components. Considering that the testbed is being developed specifically for re-engineering parts of aging systems, it is imperative to conduct fatigue and fracture analyses to predict service life of components. The fatigue life of a component can be divided into three main stages: crack initiation, crack propagation, and fracture failure [25]. The *crack initiation life* computation (Stage I crack) predicts where and when the crack will start due to cyclic loads. The *crack propagation life* computation (Stage II crack) predicts direction and rate of crack growth. And the *fracture mechanics* (Stage III crack) predicts the size of the crack that leads to an unstable growth and finally a catastrophic failure under a given load. The crack propagation and fracture mechanics are useful in obtaining safety assessment of parts in aging systems.

There are two major classes of dynamics fracture problems: (1) fracture initiation as a result of dynamic loading, and (2) rapid propagation of a crack [26]. In the latter case the crack propagation may be initiated either by quasi-static or rapid application of a load and may get arrested after some amount of unstable propagation. The quasi-static crack initiation and propagation theory has been well developed. The strain-based approach, which is based on this theory, is widely employed for crack initiation life prediction subject to external and inertia loads with variable amplitudes. The computation of the mechanical fatigue life consists of two parts: the dynamic stress computation and fatigue life prediction. Critical plane method, which is sophisticated but more general, is usually employed for computing fatigue life under multi-axial stresses [27]. The strain-based approach is demonstrated (Figure 8) using a lower control arm of the High Mobility Multipurpose Wheeled Vehicle (HMMWV) with experimental validation [28].

The most critical data for any structural analysis is the validity of the external loads. It is very important to collect a good set of dynamic loads for fatigue and fracture life prediction. Very often, the loads can be estimated by measuring strains of structural components while operating the mechanical system in a realistic environment and following a designated scenario. On the other hand, the loads can be calculated by creating multibody simulation models and by simulating the operational conditions in a virtual environment, especially

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during design process when the prototype system is not available yet. In the testbed, dynamic simulations are conducted using COTS tools such as *DADS* [29] or *ADAMS* [30]. The load history data collected from dynamic simulations and the FEA results can be transferred to the fatigue life prediction software, such as *MSC.Fatigue*, the computational code developed by *nCode International Ltd* [31]. Since the nature of the loading is random, rainflow cycle counting technique is used to count number of stress cycles. The time-history of the loads is associated with the stresses obtained from the FEA results using a special module in *MSC.Fatigue*. A plasticity correction method, such as Neuber or Seeger-Beste method is applied to account for the plastic strains during the crack initiation analysis. Based on all this information, *MSC.Fatigue* carries out the crack initiation analysis and computes fatigue life of the component.



(a) HMMWV CAD model    (b) HMMWV suspension subsystem    (c) Dynamic simulation model



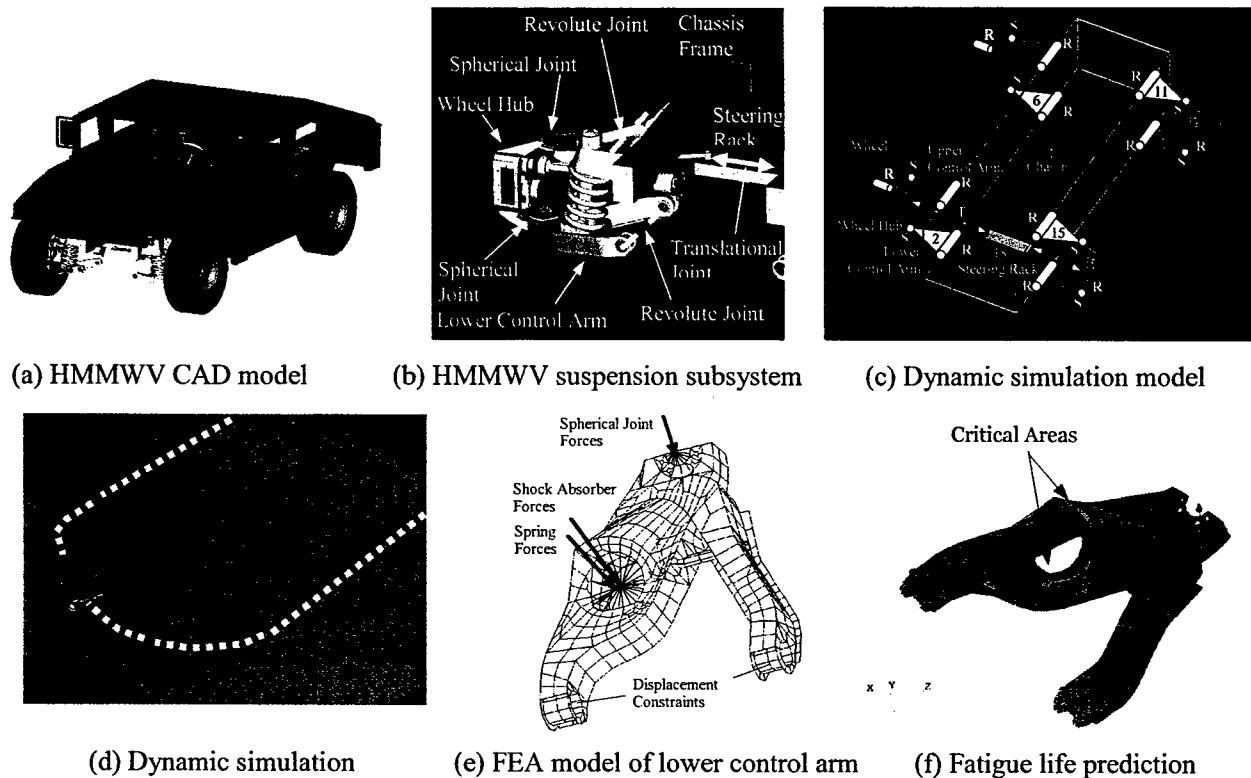(d) Dynamic simulation    (e) FEA model of lower control arm    (f) Fatigue life prediction

Figure 8  Multibody dynamic simulation and fatigue life computations

As shown in Figure 8a to 8c, a CAD model of the HMMWV suspension was constructed and converted into an 18 body dynamic model [32]. The dynamic simulation was conducted in *DADS* (Figure 8d). The finite element model of the lower control arm was constructed (Figure 8e) and dynamic stress was calculated and counted for fatigue life calculations. Looking at the plot of fatigue life, as shown in Figure 8f, it is clear that the crack is most likely to initiate from the area near the shock absorber mounts.

Stage II crack growth is governed not by the local shearing stress but by the maximum principal stress in the neighborhood of the crack tip. Thus the crack tip deviates from its slip path and propagate in a direction roughly perpendicular to the direction of the maximum normal stress. When the crack length reaches a critical size, one additional cycle causes complete failure, i.e., the Stage III crack. The linear elastic fracture mechanics (LEFM) [26] is usually employed to quantify the material fracture behavior. If the strain is not significant (<2%), LEFM works well for most of the problems. For impact-induced fatigue and fracture, the structural responses usually extend into non-linear and plastic ranges. In addition, dynamic fracture mechanics contains three complicating features that are not present in LEFM and elastic-plastic fracture mechanics: inertia forces, rate-dependent material behavior, and reflected stress waves. In certain problems, one or more of the above effects can be ignored. If all three effects are neglected, the problem reduces to the quasi-static case. The theoretical framework of elastodynamic fracture mechanics is fairly well established. Most of the commercial

software tools are able to solve quasi-static and elastodynamic fracture problems for classical 2-D models or regular 3-D geometries based on LEFM theory.

*Future Research*

However, propagation of a crack in an arbitrary 3-D solid under the influence of dynamic or impact load remains a challenge. The combination of Extended Finite Element Method (X-FEM), which is used for modeling voids in a structure and Level Sets Method (LSM), which is used to model moving interfaces, was recently employed for modeling crack growth in an arbitrary 3-D solid [33,34]. The X-FEM is used to compute stresses and displacement in a structure containing cracks or voids. The fact that XFEM does not require re-meshing makes it very attractive for modeling crack growth. Further, it does not require crack to conform to the finite element mesh as the crack surfaces are represented in terms of level set functions defined at nodes of the finite element mesh. Application of this combined X-FEM and LSM for modeling crack growth in an arbitrary 3-D solid was successfully shown in [33,34]. The integration of the X-FEM and LSM method into the testbed for solving crack propagation problems under the effect of dynamic and impact loads is being investigated. In addition, shape optimization technique must be developed using the X-FEM and LSM to support design for fracture mechanics of 3-D applications.

## 2.4 Manufacturing

Machining and forming are the two primary manufacturing processes for fabricating a broad range of mechanical parts and subsystems in air logistics centers. Forming is often employed to fabricate shell structures (aircraft skin panels), and machining is employed either to directly cut the mechanical parts or to fabricate dies or molds. Virtual manufacturing is a simulation-based method that supports engineers to define, simulate, and visualize the manufacturing process in a virtual environment, thereby reducing time lost in trial and error and ultimately, cost. The objective of the fast prototyping capability is to support the logistics centers to produce physical samples and functional replacement parts of small quantity in a short turnaround time and thus make manufacturing cost-effective. Therefore, following three capabilities related to manufacturing are included in the testbed: metal forming and virtual machining simulation, rapid prototyping (RP), and CNC machining.

*Virtual Manufacturing Simulations*

For the forming simulations, three tools—*Optris* [34], *FastForm 3-D* [35], and *Dynaform* [36]—were investigated. All three of these software packages provide excellent modeling and simulation capabilities that would greatly speed up the design and manufacture processes by reducing trial and error runs for production of molds and templates, reduction of finishing operations such as trimming, and also by eliminating much of the manual labor. An air conditioning duct shown in Figure 9a from a C-135 airplane was employed for this study. This part was to be made using 0.080 inch thick stainless steel, and was to be formed in three pieces (Figure 9b). Simulations of the forming process were conducted using all three software tools (for example Figure 9c). From these simulations, it was possible to identify and correct the areas of wrinkling and tearing before any actual production of parts was carried out (Figures 10d and 10e). Among the many benefits, the most important was cost reduction. This was due to a substantial decrease in trial and error, which in turn also reduced material waste and decreased time spent testing actual template and die designs. It also allowed for rapid changes in variables such as die shape and movement, stamping forces and speeds, followed by a simulation of the updated design. Through the completion of this study it was proven that given a part, mold or die designs and template designs can be generated by applying various existing software packages. In addition, using the computer generated dies and templates, and by comparison between packages, reasonably accurate forming simulations can be performed that would aid the forming manufacturing.



(a) Physical sample    (b) Parts to be formed in three pieces    (c) Forming simulation in *DynaForm*



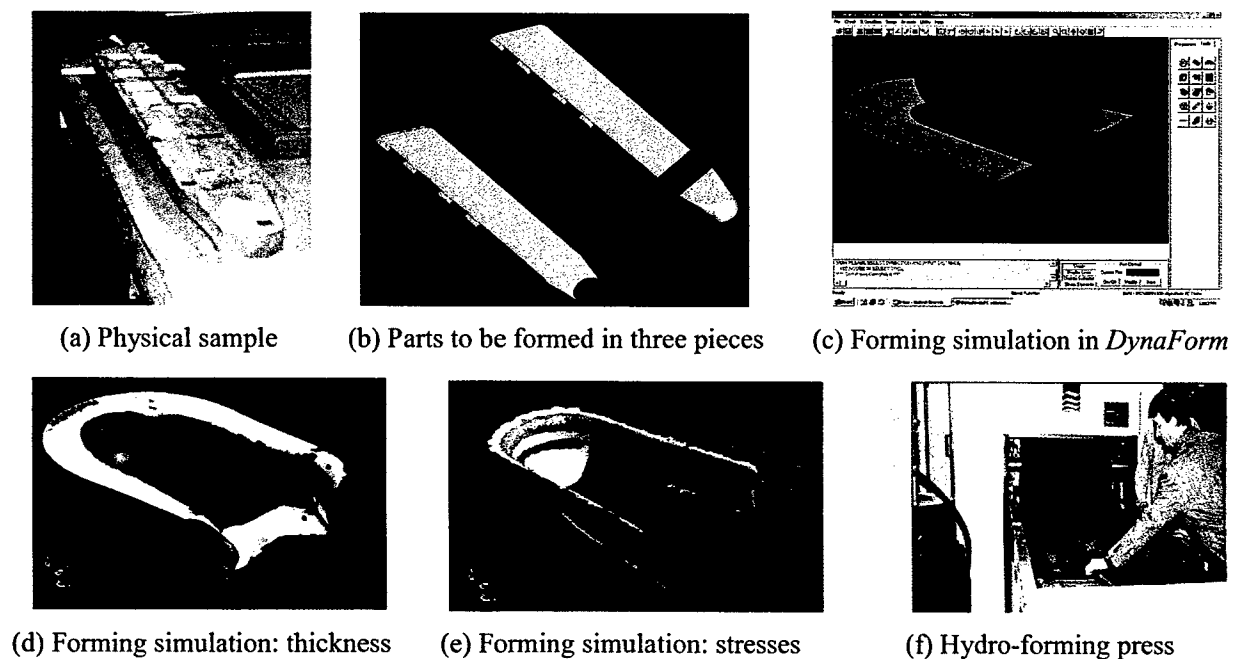(d) Forming simulation: thickness    (e) Forming simulation: stresses    (f) Hydro-forming press

Figure 9  Metal forming for the nose cone of the air duct

For CNC machining simulation, *MasterCAM* [38], *Pro/MFG* [24], and *CATIA* were included in the testbed. The machining process of the AWACS torque tubes was simulated using both *Pro/MFG* and *CATIA*. Figure 10 shows the virtual machining process for the torque tube in *CATIA*. There were total 5 operations involved. Each operation consisted of 2-4 NC sequences, usually a rough volume milling to remove material using a larger cutter, followed by local milling to clean up remaining material using a smaller cutter, and surface milling to polish the machined surface to meet the surface finish requirement, usually characterized by the scallop height. For the torque tubes, the final overall surface finish was 0.01 in. The machining sequences were simulated in computer for verification. The total machining time for the torque tubes, excluding the set-up time, was about 60 hours. The virtual machining model was used to generate CNC tool path, which was then transferred to a HAAS VF0E4 CNC milling machine [39] and a functional prototype was fabricated (Figure 10f).
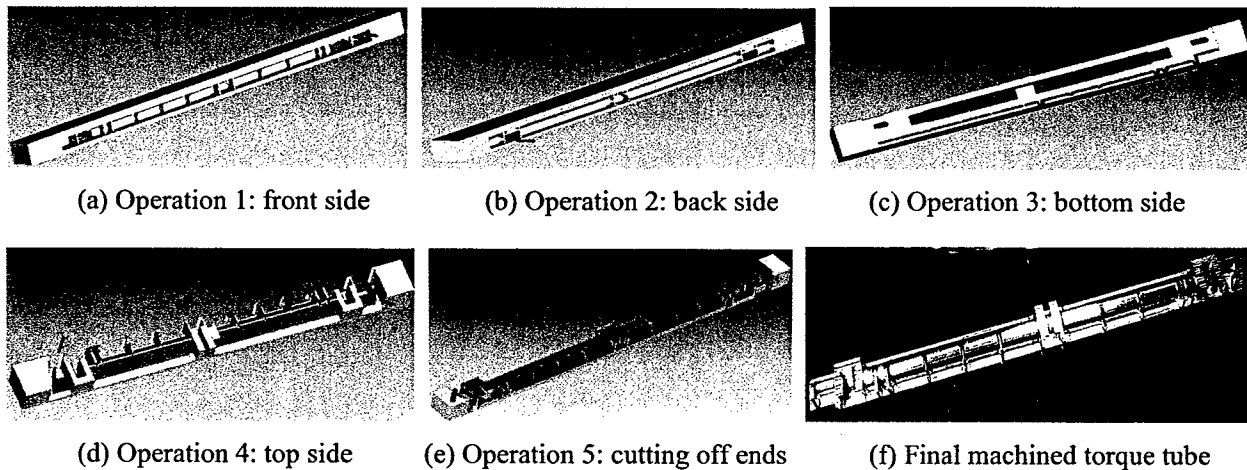


(a) Operation 1: front side     (b) Operation 2: back side     (c) Operation 3: bottom side

(d) Operation 4: top side     (e) Operation 5: cutting off ends     (f) Final machined torque tube

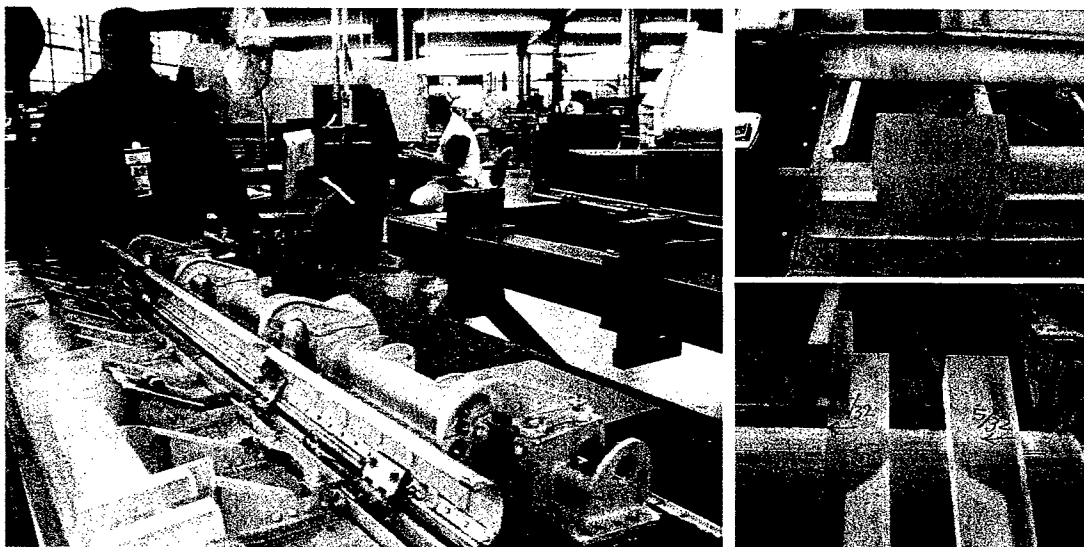Figure 10  Virtual machining of an E-3 torque tube



Figure 11  Verification of geometric accuracy using the physical prototype

*Rapid Prototyping*

The RP technology supports fabrication of physical sample parts directly from CAD solid models without tooling or fixtures. Currently, the *ModelMaker II* [40] from Solidscape, Inc. is included in the testbed.
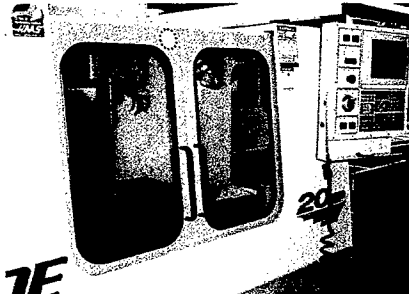
In addition, other RP technologies and machines, such as StereoLithography (SLA) and Selective Laser Sintering (SLS) [6] are available commercially from vendors, such as American Precision (www.approto.com). The RP machines support fabricating physical prototypes of the redesigned parts, which can then be mounted on fixtures to validate their geometry. In addition, the physical samples can serve as plastic or wax patterns to produce functional parts in a small quantities using, for example, investment casting. Use of RP technology was made in reverse engineering the torque tubes. An STL model was created based on the torque tube CAD model. The STL file was sent to American Precision and the physical prototype of the tube was received in just three days. Figure 11 shows the physical prototype of the torque tube fabricated using SLA 7000 machine. This prototype was delivered to OC-ALC, and was then mounted on wing panel fixtures to verify its geometric accuracy.
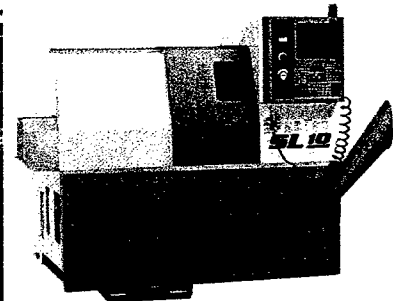
*Manufacturing Facilities*

Currently, there are two HAAS CNC mills and one CNC lathe together with other traditional machines available for the testbed, as shown in Figure 12. These facilities provide an excellent and powerful capability for support of producing functional prototypes or replacement parts in a small lot size for aging systems.



(a) Conventional machines in shop      (b) HAAS VF-series mill      (b) HAAS CNC lathe

Figure 12  Manufacturing facilities in testbed

*Future Research*

The forming and machining simulation capabilities together with the prototyping and manufacturing facilities integrated in the testbed are capable of manufacturing functional parts and physical samples in a short turnaround time. The CNC machines are capable of producing accurate parts in a small quantity in a cost effective way. More virtual manufacturing capabilities, such as casting and welding, and manufacturing equipment, such as laser cutting devices, are being added to the testbed to broaden its applications.

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# 3. SYSTEM INTEGRATION

Basic steps of re-engineering and reverse engineering include 3D scanning, point cloud manipulation, surface modeling, feature recognition, solid modeling, and analyses to ensure performance. In order to efficiently accomplish the design tasks in each step, advanced computer based tools are required. These heterogeneous tools usually use different file format and work on different platform, leading to the difficulty to be integrated in one design environment. In this project, the focus is not on converting file formats or interoperability of CAD/CAM/CAE software, rather the focus is on selecting proper available commercial software and allowing the built-in compatibility of the software to meet the integration needs in reverse engineering, re-engineering, and manufacturing. Consequently, various CAD/CAM/CAE software tools have been tested and a set of software have been identified to perform engineering design tasks. These set of software work together and can be incorporated in one design environment.

After exploring different reverse engineering, re-engineering, and manufacturing solutions and corresponding software tools, a number of modeling approaches and a corresponding set of tools were identified and tested (see Section 2). These sets of solution ensure compatibility of file formats between different reverse engineering, re-engineering, and manufacturing steps. The main purpose of the integration system is to verify that by choosing a typical reverse engineering or re-engineering solution, and utilizing recommended tools, the project can be implemented smoothly. An instance of our integration system is the testbed, which is used to demonstrate the feasibility of the integrated system as well as our reverse engineering, re-engineering, and manufacturing solutions and software selection.

## 3.1. Integration Requirements

The integration system needs to satisfy the general reverse engineering, re-engineering, and manufacturing project needs. In re-engineering and reverse engineering projects, the point cloud and other CAD files usually have large size. Consequently, exchange of design information is not as easy as sending an email. Product management must be supported by the system to share and manage files or documents. The product data management needs to include version control, access control, and organization of documents in a folder structure.

Some product management requirements for the integration system are: (i) the product data and model should be managed in a structure through which a designer can easily find the product data; (ii) basic file access controls are required to keep the data secure and restrict illegal operations; (iii) the design system is required to provide some basic functions to manage the file operation privileges based on designers' roles in the team; and (iv) various file status needs to be supported by the design system to prevent the file inconsistency, which may occur when two users modify the same file simultaneously.

Most reverse engineering and re-engineering solutions involve multidisciplinary design activities. Point cloud manipulation is a special ability of CAD system that does not have wide applications other than reverse engineering and re-engineering. Surface modeling has some applications in contour design and solid modeling needs to consider the engineering conditions, such as boundary and loading conditions. Successful reverse engineering or re-engineering of a product requires knowledge of multiple disciplines; as a result, multiple engineers and designers are required to complete the design tasks. Design collaboration is therefore required for typical reverse engineering and re-engineering projects to allow multiple designers in different disciplines play their roles. Collaboration can help reduce unnecessary iteration in design.

Design collaboration, in the integration system, is based on two kinds of interactions among the design team members: asynchronous and synchronous. Asynchronous interactions involve email, notification, forums, as well as sharing documents where the receiver is not required to respond in real-time. During synchronous interactions, the receiver is required to respond in real-time. Examples of synchronous interactions include white board, chat room, model viewer, video/audio communication, and so on. A summary of the possible design collaboration and its corresponding design phases in a reverse engineering project is listed in Table 1.

Table 1  Collaboration in Reverse Engineering and Re-Engineering

| Project Phases | Design Collaboration |
|---|---|
| Information collection | Share field measurements<br>Share existing engineering documents<br>Notify the method of point cloud scanning |
| Requirement clarification | Discuss estimation method of load condition<br>Discuss work environment of component<br>Discuss project objective |
| Point cloud manipulation | Import point cloud data<br>Discuss with CAD Engineer about feature segments<br>Share extracted point clouded with CAD Engineer |
| CAD model creation | Import extracted point cloud data<br>Discuss with manager about possible component improvement<br>Discuss with manager about quality of obtained model |

In most engineering projects, some of the activities can be performed concurrently. The concurrency of tasks helps reduce the project completion time and thus lowers the cost. The workflow management of the integration system allows planning, scheduling, and execution of the concurrent design tasks.

Organization management is another system requirement related with the task scheduling. Organization management includes distribution of tasks according to skills of the designers. The integration system automatically distributes the design tasks to the designers with certain professional skills. The manager is allowed to obtain the information related to expertise of his/her staff and manually make the decision to assign tasks.

The workflow management and organization management in the integration environment requires implementation of privilege control. In any project, each team member has his/her unique roles in the project. As an example, the system should not allow every team member to modify the workflow or organization information. Usually only the manager of the project should have this privilege. The manager should be allowed to setup the organization and workflow, start the project, and dynamically monitor and control the organization and task schedule. The integration system should provide basic functions, such as user management and task management. Based on the user management, only permissible users can perform administrative tasks. Whereas, based on task management, design tasks are assigned to the relevant users according to the schedule.

Workflow templates for the reverse engineering and re-engineering processes are created by analyzing the different software tools that will be used in different steps of the engineering process. This workflow is utilized to organize a typical reverse engineering or re-engineering project, assign the tasks, instruct the exchange of data file, and gather a real-time collaboration for team members. This workflow management software is usually called product lifecycle management (PLM) in current software industry. It can support multi-disciplinary and concurrent engineering philosophies. In an integrated engineering environment, the project will be organized according to concurrent and multidisciplinary engineering requirements. In addition, design collaboration is a key issue for the integrated reverse engineering, re-engineering, and manufacturing environment. Based on these assumptions, if the designers in different disciplines are required to work together, performing tasks sequentially and in parallel, the environment needs to support sharing of design information and CAD models for multiple engineers and to allow discussions among each other to make decisions and avoid conflicts.

## 3.2. Integration System Architecture

To satisfy the integration requirements presented in Section 3.1, the system consists of four major components: product management, organization management, workflow management, and real-time collaborative design tools. Each component of the integration system is supported by a database (Figure 13).
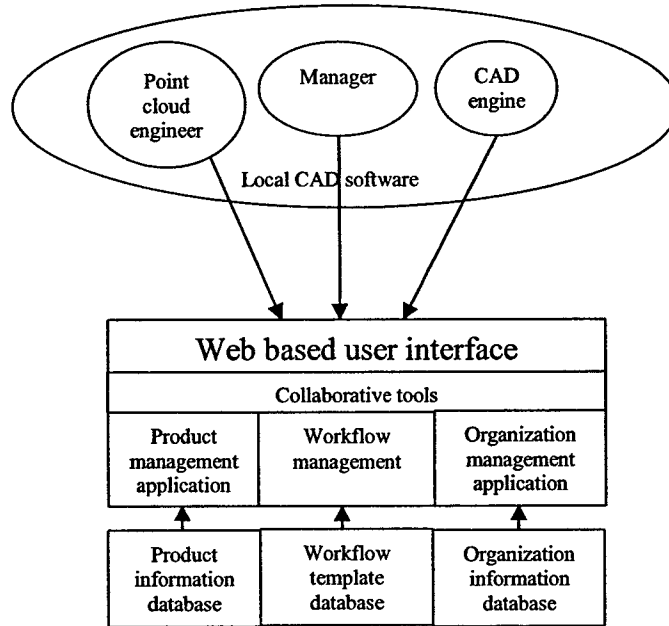


Figure 13  Integration system architecture

*Web-Based User Interface*

To support multidisciplinary teams to work together, a web based user interface is essential. Designers that are geographically distributed log into the system with their own accounts and are automatically assigned with proper administration privileges. The web user interface is an entry for designers to access all system functions. It has links on the webpage to let the users explore different collaborative tools and management functions.

After a user logs into the system, three types of information are provided: (i) the user can check the new tasks that have been assigned and the progress of current working tasks, (ii) the user can check his/her workspace and find all the data files that are needed to perform the tasks, and (iii) the user can utilize the collaborative design tools to discuss problems and issues with other team members. Powered by the web interface, the integrated system supports distributed users collocated, within the design environment, collaboratively anticipating design process through a web-based design system.

*CAD and Other Reverse Engineering Software*

CAD software is also a part of the integrated system. A selected set of tools are utilized in various reverse engineering, re-engineering, and manufacturing design tasks. In the integrated system, wrappers that can be used to incorporate legacy CAD systems into the design environment are not utilized. All CAD systems are installed in client's local computers and the generated CAD and analysis models are uploaded into the server to inform other members of the team of the results. The same principle is applied for other tools required to perform different reverse engineering, re-engineering, and manufacturing design tasks.

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*Collaborative Tools*

For reverse engineering and re-engineering projects, determining features that are needed to recreate the model of an existing component and identifying feature creation methods needed to create these feature geometries, is an important decision. In the case of complex components, different design considerations need to be taken into account. The expectation is to create a solid model that later can be easily modified to achieve design improvements. For this goal, point cloud engineer, CAD engineer, and manager all need to collaborate and agree on features that will be created. The collaborative tools in the integrated environment are designed to assist designers' discussion to allow complete understanding of other designers' ideas.

*Management Functions*

In order to manage a design project, product lifecycle data need to be stored and shared with all engineers who are involved in the project. Organization and workflow management are also needed. In addition, the system needs to support multiple teams and designers in different disciplines to work simultaneously.

The implementation of the integration system is focused on collaboration. Even though, the COTS software are used to manage a reverse engineering project, the collaborative tools, especially real-time design tools that allow a group of people work together, are still not suitable to support reverse engineering, re-engineering, and manufacturing applications. The implementation of the integrated system is based on common online platforms such as Java and Macromedia studio so that the client installation can be simplified. Details about the setup of the integration are provided in the next section.

## 4. TESTBED AND TESTBED DEMONSTRATION

### 4.1 A Brief Summary on Testbed

In order to evaluate and demonstrate the reverse and re-engineering processes and concepts of integration, a testbed has been developed. The testbed is capable of supporting all activities required to perform reverse engineering and re-engineering of aging aircraft components, which includes manipulation of scanned points, creation of surface models of component, creation of parametric solid model of the component, improvement of components while considering multiple performance issues, generation of manufacturing processes, and development of prototypes. Table 2 lists engineering capabilities, software tools, and equipment included in the testbed.

Table 2  Software, prototyping, and manufacturing capabilities included in the testbed

| Tasks | Engineering Area | Software/Tool | Remarks |
|---|---|---|---|
| Reverse Engineering | 3D Scanning devices | Laser Scanner, CT Scanner, etc. | Various vendors |
| | Surface modeling | *Imageware, GeoMagic, ICEM, Paraform, CATIA Surface* | Further development |
| | Solid Modeling | *SolidWorks, CATIA, Pro/ENGINEER, I-DEAS, AutoCAD* | |
| Re-Engineering | Dynamic simulations | *DADS, ADAMS* | |
| | Fatigue Life | *MSC/Fatigue* | |
| | Crack Propagation | XFEM, *MSC/Fatigue* | Research |
| | Shape Optimization and FEA | *CosmosWorks, MSC/NASTRAN, Pro/MECHANICA, ANSYS* | |
| Fast Manufacturing | Rapid Prototyping | SLA, SLS, 3-D Printing, etc. | Various vendors |
| | CNC | *MasterCAM, Pro/MFG*, CNC mills, CNC lathe | 30"×16"×20" |
| | Forming | *DynaForm, FastForm, Optris* | |
| System Integration | | *Windchill* | |

As shown in Table 2, the proposed testbed involves using different techniques, technologies and software. In order to facilitate the reverse engineering, re-engineering and, manufacturing design process, an integrated environment is essential. Consequently the engineering testbed needs to support:

- Developing reverse engineering methodology based on available commercial software,
- Redesign components to satisfy engineering needs from parametric models,
- Building an integrated design environment to support design activities in typical reverse engineering and re-engineering projects,
- Support both synchronous and asynchronous collaboration among a set of team of engineers. The focus is on engineering data and information.

The developed design environment is software independent and can support multiple users who are geographically dispersed. This principle extends to all reverse engineering, re-engineering and manufacturing activities, data, and collaborative activities, and well as to the infrastructure design.

In the service of these goals, almost all design activities can be performed in a range of commercial software and manufacturing capabilities (Table 2). Most of the activities, other than collaborative meetings, are performed by experts in their local computers with commercial software. These activities are computationally expensive and require time to complete. Each engineering activity in the testbed has detailed information on the accepted outcome for the user. Once an activity is completed, the generated information is uploaded in the testbed for other members of the team to access, evaluate, and modify as required. To facilitate in ubiquitous

access of the testbed, distribution of the reverse engineering tasks and the interface to the process and product data management rely on Web browsers. In order to access the testbed, the team members (client-side) needs to install several browser plug-ins, e.g., *Cortona VRML*, *Macromedia Director*, and *Windchill Productview* plug-in.

The testbed is setup using simple client-server architecture (Figure 14). The server, which includes *Windchill* and communication, is connected to the Internet. The clients access information about the product and reverse engineering information from the servers using a web browser environment. Files are uploaded to the server by the team members once the tasks are completed. Using web-based interfaces team-members can access all product related data.
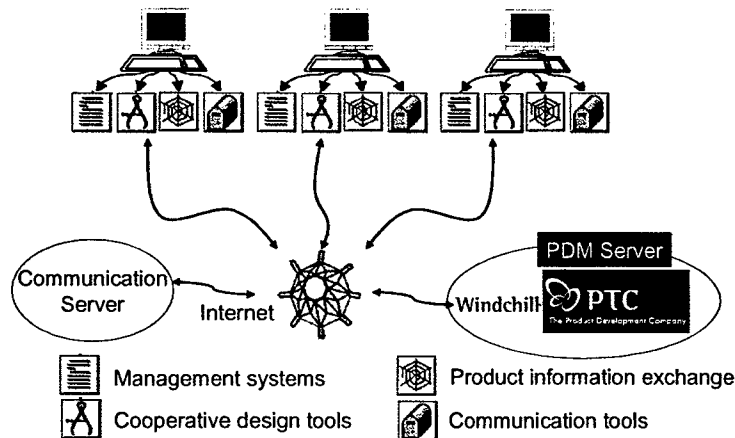


Figure 14 Testbed setup

The real-time collaborative meeting tool uses a communication server to ensure that real-time synchronization is achieved for a set of geographically distributed team members. The overall tasks supported in the testbed are shown in Figure 15. The three general categories of tasks supported by the testbed are: (1) organization and distribution of tasks, (2) reverse engineering activities, and (3) product information exchange.
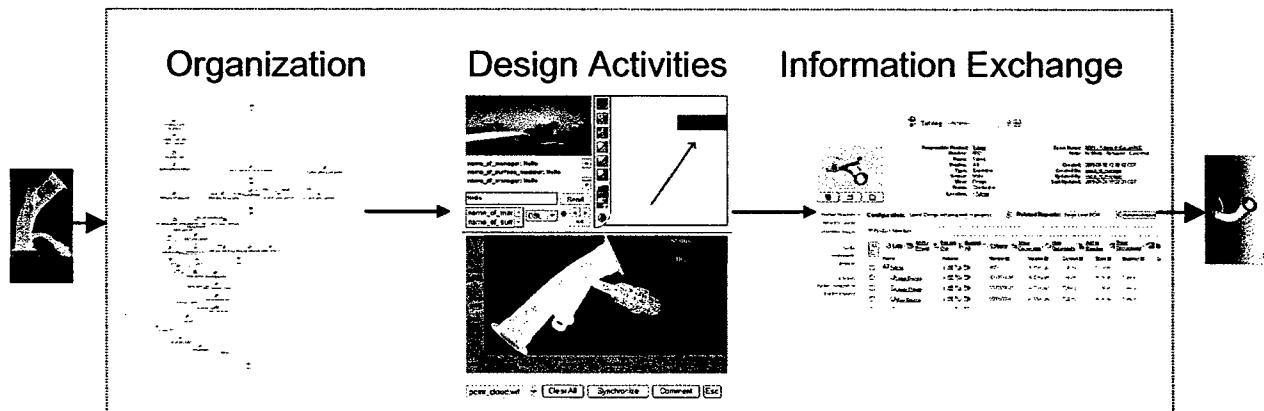


Figure 15 Overall tasks supported in the reverse engineering testbed

*Organization and Distribution of Tasks*

The testbed is built using *Windchill*, which is a Product Life-cycle Management software from PTC. The three components to organize and distribute reverse engineering activities are:

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- *Windchill* workflow template: The template provides a structure to accomplish reverse engineering and re-engineering projects. The template can be copied and modified to suit the needs of any specific reverse engineering and re-engineering process. The template includes flow of activities, details for each engineering activity, and general information related to different engineering processes, etc (Figure 16). The workflow template provides possibilities to simulate, observe, and improve reverse engineering and re-engineering processes.
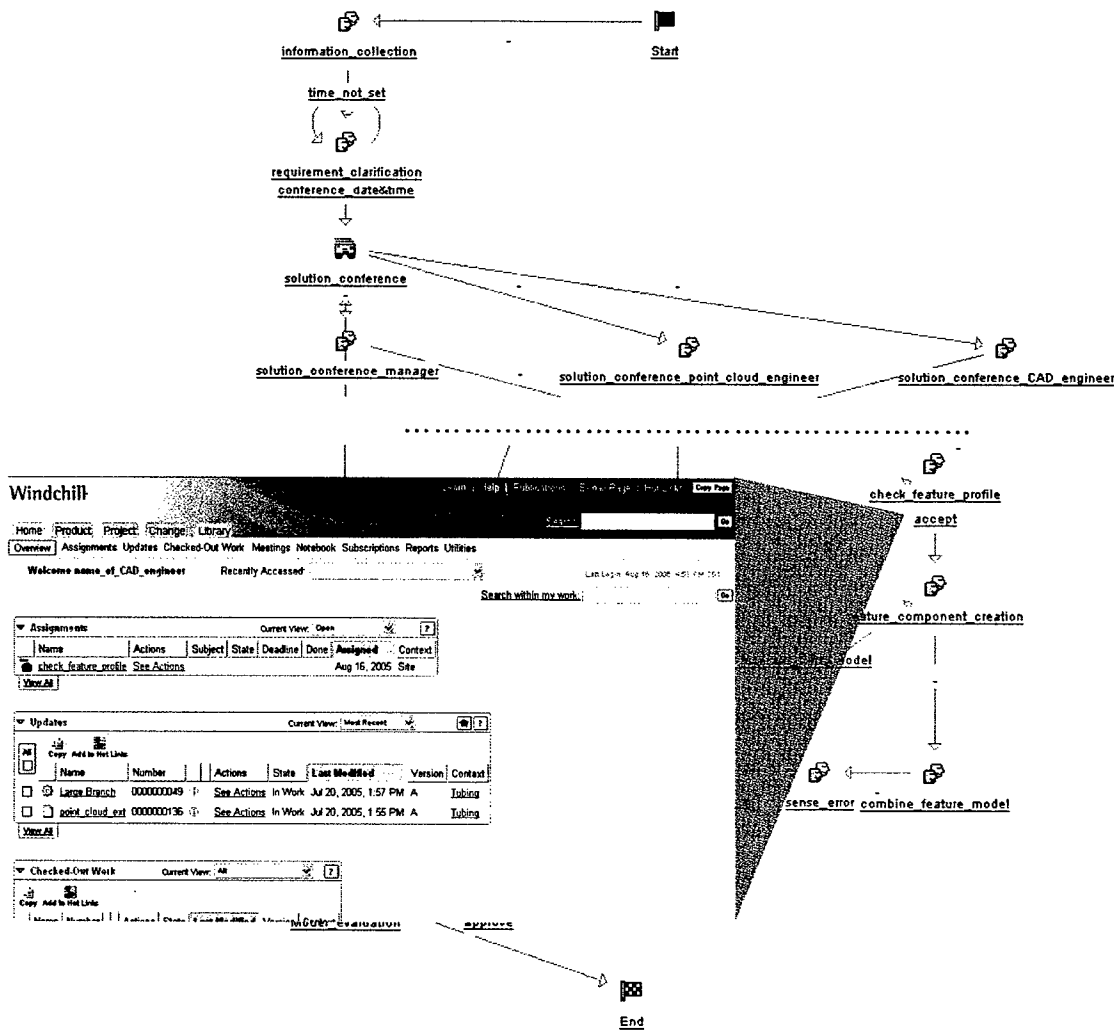


Figure 16  Activity flow and distribution of tasks in the testbed

- A simplified process model with activities and precedence connections: The flow of activities represents the tasks that need to be performed to reverse engineer products. The testbed supports automated notification of task completion and distribution of task to appropriate team members. Team members can access detailed description of their current tasks using the web-based interface. The process flow model supports with sequential and parallel tasks, along with scheduling of ad-hoc activities that might be required for successful completion of the project.

## Design Activities

The design activities supported on the testbed include support for both asynchronous and synchronous activities. The asynchronous activities are performed in the local computer of the team-members, with the data

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uploaded in *Windchill* once it is completed. In order to support real-time collaboration, a web-based tool has been developed (Figure 17). This collaborative tool supports text messaging, audio, video, sketching, and viewing of 3D models in real-time to facilitate activities required for meetings. The 3D viewing module has the capability for all users to have real-time synchronous view of the model. To enhance collaboration among different members of the team, the collaborative 3D model viewer allows users to add notes to the 3D model, and exchange text and audio information in real-time. Collaborative meetings, if needed, can be scheduled in an ad-hoc manner. When a meeting is scheduled, appropriate group members are sent an email that has the web-link to the collaborative tool and the scheduled meeting time. At the scheduled time, all group members can log into the collaborative tool to discuss issues related to the project using the web environment.
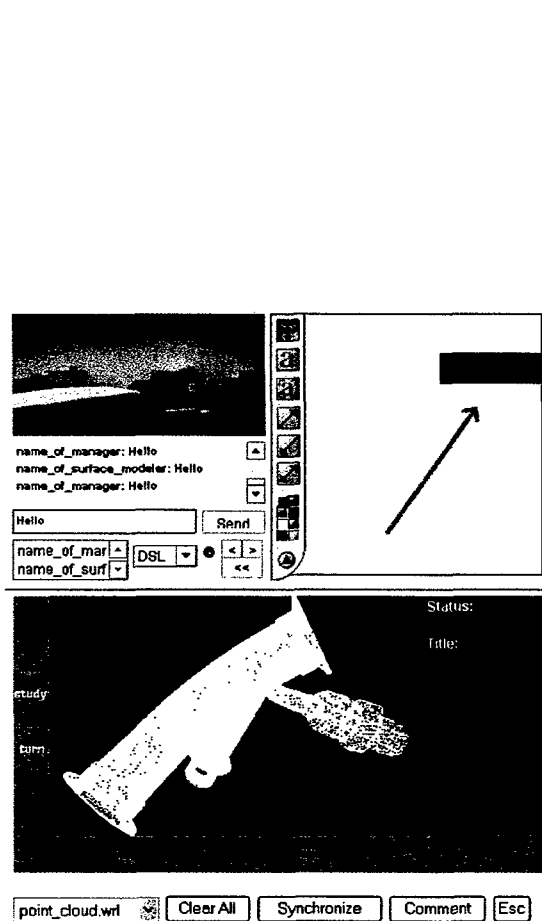


Figure 18  Product structure for the tubing reverse engineering example.



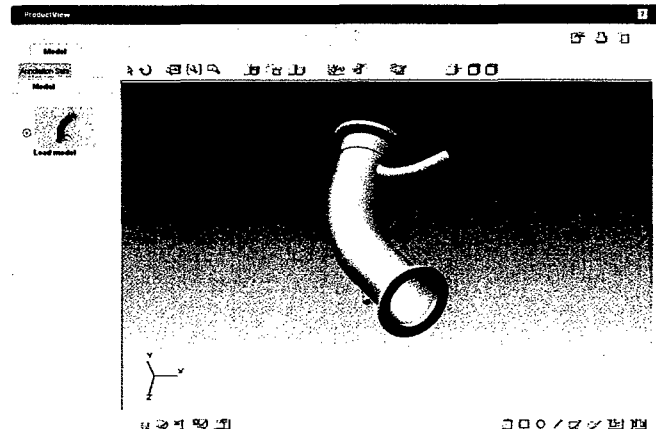Figure 17  Real-time collaborative tools for meetings



Figure 19  3D view of artifact being reverse engineered

*Product Information Exchange*

Product information in the testbed is arranged through a folder structure and a product structure. General information related to reverse engineering and description of the project is saved in several folders. Information related to the component is organized according to the product structure (Figure 18). Solid models of components uploaded in the testbed are also automatically converted into a web-based viewable format for *Windchill* viewer (Figure 19). Team members can access, view, and download the files from the testbed as needed to complete their activities.

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## 4.2. Testbed Presentation and Demonstration

The testbed was presented and demonstrated to personnel from OC-ALC on November 30, 2005 (Figure 20). A list of participants, call for meeting, and meeting agenda, etc., are summarized in Appendix A. In order to evaluate the testbed, two case scenarios were created. The reverse and re-engineering scenarios highlight: (1) a systematic reverse engineering approach, (2) an enhanced ability of collaboration among team members, and (3) a customized *Windchill* product management system. The scenarios were utilized to demonstrate the testbed.
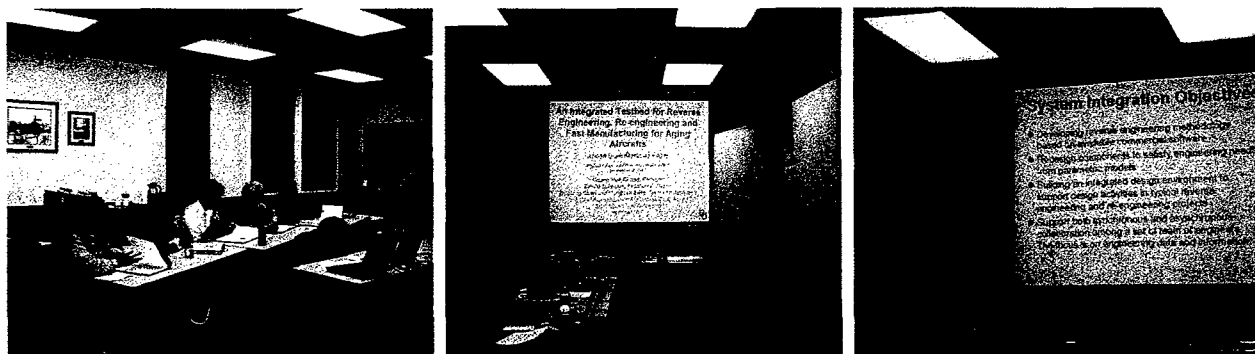


Figure 20  Testbed presentation and demonstration meeting held on November 30, 2005 at OU

The reverse engineering of the B-52 de-icing tubing scenario involved an engineering team consisting of four members, who are geographically distributed: a Manager, a CAD Engineer, and two Point Cloud Engineers. A template with a flow of activities (see Figure 15), along with appropriate instructions were setup in the *Windchill* environment. This template was the starting point for the manager to initiate the reverse engineering project. The initial steps for the manager involved gathering product information, constraints, and point-cloud data. Once the information was gathered, the manager created the team and called a meeting in the integration framework using the real-time collaborative tools (Figure 17) to discuss details of the project. After the meeting an appropriate reverse engineering process was selected and modified according to the requirements and needs of the project. The integration framework then supports accomplishing these tasks by appropriate users. Information and instruction on how to complete the different tasks were also available to the users from the environment. Information created from each activity was uploaded in the environment for other members of the team to view, access, evaluate, and use (Figure 18). These data are organized in a set of defined folders that follow the product structure to reduce the effort of finding the files (Figure 19). The progress of the project could be monitored by any member of the team at any given time. After each task was completed, the environment sends appropriate notification to relevant team members to proceed to the next.

The second scenario involved re-engineering of an E-3 torque tube. The team consisted of three geographically distributed team members working on the project: a Manager, a CAD Engineer, and a Manufacturing Engineer. A template delineating flow of design activities and related information was available to the manager to initiate a re-engineering process. The manager gathered initial data related to the project, which included general information related to the problem and a CAD model. A meeting using the system was then called to discuss issues related to the project, including selection of material for the torque tube. Once the discussion was complete, the CAD designer performed FEA on the model to evaluate structural performance and manufacturing engineer performed virtual machining (VM) to ascertain machinability and estimate machining time. Design sensitivity coefficients (gradients) of the objective and constraint functions were computed and discussed between the CAD and Manufacturing engineers to determine design changes, which were used to update FEA and VM models. Once all design changes were made and the files were submitted, the manger called a meeting to finalize the design. Similar to the reverse engineering process, information generated in each design task was organized in pre-defined folders. Progress of the project could be monitored using the system.

In order to conduct a preliminary evaluation of the testbed the scenarios were demonstrated to several engineering personnel at OC-ALC. Participants for the demonstration were selected based on their experience and knowledge on reverse engineering at OC-ALC. A survey was conducted at the end of the demonstrations. The raw data from the survey is shown in Table 3.

One senior personnel from OC-ALC mentioned that the reverse engineering technology was discussed at OC-ALC for some time, but it was the first time that he saw a reverse engineering process so clearly laid out. He suggested the research team to seek a patent for the process. In addition, he suggested that the research team at OU should work with OC-ALC engineers and a contract vehicle should be established to channel the reverse engineering tasks to OU, so that the testbed facilities can be used their fullest extent and OC-ALC's MRO missions can be supported more efficiently. Some of the concluding remarks that can be formulated from the survey and discussions during the demonstrations are:

- Knowledge related to reverse engineering process is available. Need to establish a process to archive completed reverse engineering processes, so that it can be used for other projects.
- Integrated real-time design tools to support collaboration. The tool opens up avenues to conduct collaborative projects among OC-ALC personnel, researchers at University of Oklahoma, and others.

Table 3  Demonstration survey

Scale used for response:

| 1 | Strongly Agree | 2 | Agree | 3 | Neutral | 4 | Disagree | 5 | Strongly Disagree |
|---|---|---|---|---|---|---|---|---|---|

| Q1. | Was adequate information provided on the testbed? | 2 | 1 | 1 | 1 | 1 |
|---|---|---|---|---|---|---|
| Q2. | Can reverse/re-engineering of components at OC-ALC benefit from the testbed? | 2 | 2 | 1 | 1 | 1 |
| Q3. | From the information provided during the demonstration, can the reverse engineering design method support OC-ALC's needs? | 2 | 2 | 1 | 2 | 2 |
| Q4. | From your perspective, did the integrated system considered appropriate issues and consisted of appropriate tools for reverse and re-engineering of aging aircraft components? | 1 | 1 | 1 | 2 | 1 |
| Q5. | Does the system have adequate capability to support collaboration among the members of the team? | 1 | 1 | 1 | 2 | 3 |

*Future Research*

The integration environment, coupled with synchronous collaborative tools is capable of supporting reverse engineering, re-engineering, and manufacturing projects. The integration environment can support multiple users performing sequential and parallel design tasks. A real-time reverse engineering and re-engineering project needs to be conducted using the testbed for further verification. In addition, more examples of reverse engineering and re-engineering projects can help designers provide with a knowledge base to perform design tasks more efficiently.

# 5. CONCLUSIONS AND RECOMMENDATIONS

In this report, the research results of the AFRL-sponsored research project, including an RRF testbed were summarized. The integrated testbed that supports logistics centers to conduct reverse engineering, re-engineering, and fast prototyping of aging systems and components was presented. A number of examples obtained from logistics centers were employed to illustrate and demonstrate the feasibility of the proposed RRF process using the testbed. The COTS tools and equipment were investigated extensively for constructing the testbed. The major issues identified in the reverse engineering process include the labor-intensive surface modeling, inflexible feature recognition capability, and incompatibility between NURB surfaces and geometric representation of CAD solid features. A number of development and research tasks were formulated, including fully automating the surface construction from discrete point clouds using advanced algorithms. In re-engineering, existing crack propagation capability supports classical 2-D and very limited 3-D applications. Extended FEM and LSM hold potential for extending the crack propagation calculations to support general 3-D applications. For fast prototyping, more virtual manufacturing simulations, such as casting and welding, can be added to incorporate a broader range of manufacturing process into the testbed. In integration, reverse engineering and re-engineering projects need to be performed using the testbed through collaborative efforts between OC-ALC and OU. This will provide further verification for the system. More examples of reverse engineering and re-engineering projects can help designers provide with a knowledge base to perform design tasks more efficiently.

The testbed and technology involved was presented and demonstrated to engineers and managers from OC-ALC and received very positive responses and constructive feedback. A contract vehicle is recommended to be established between OU and OC-ALC to channel reverse engineering assignments more efficiently to OU, following the suggestions of OC-ALC personnel. Once the contract vehicle is established, the research team at OU will be able to work with engineers and managers at OC-ALC simultaneously on specific tasks using the testbed facilities.

In addition, the publications are reasonably productive. The publication list includes six referred journal papers, twelve conference presentations and proceedings, five project reports, and two MS theses. Details can be found in Appendix B.
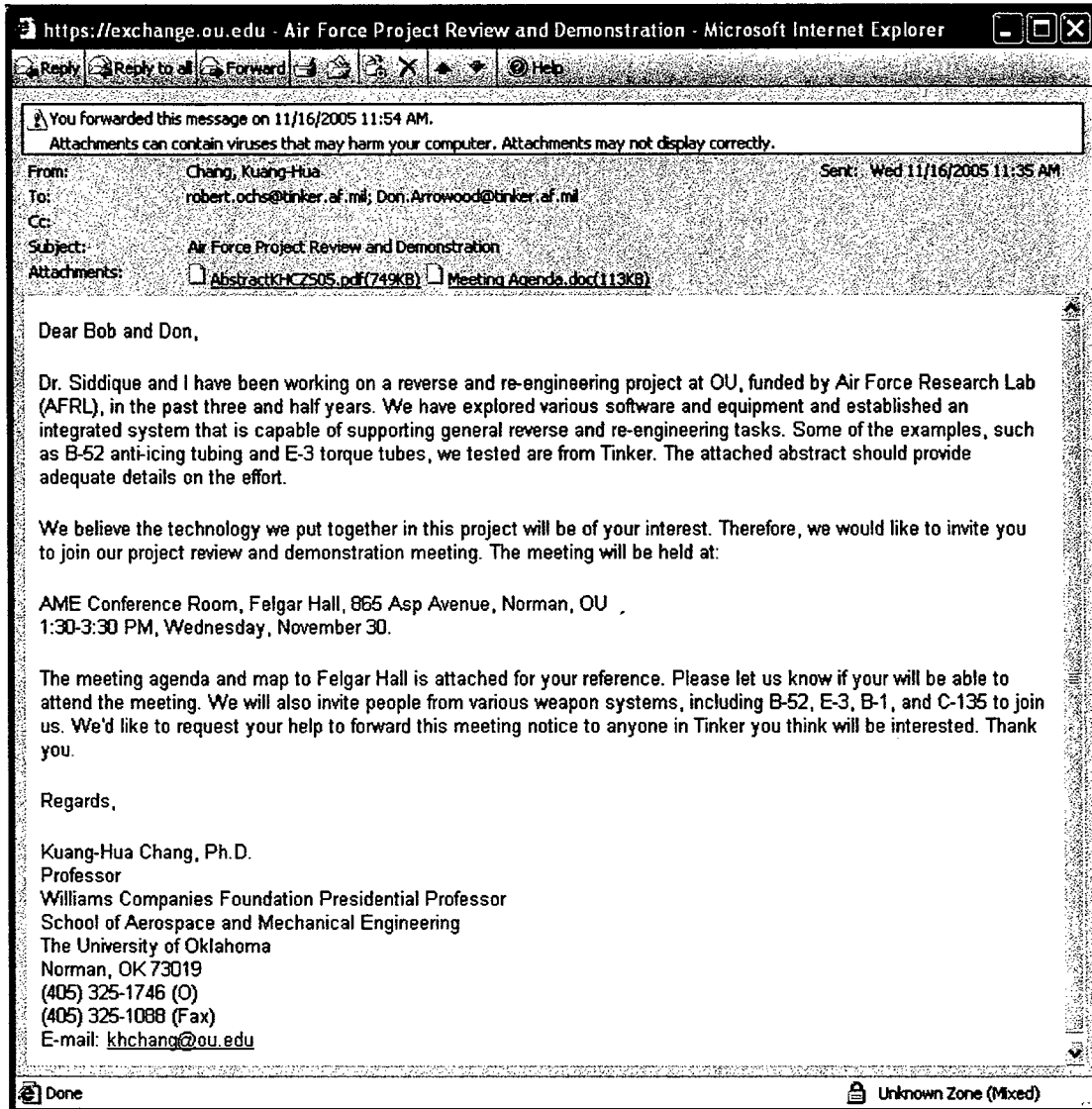
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13. Raindrop Geomagic, GeoMagic Studio, Research Triangle Park, North Carolina 27709. www.geomagic.com
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http://www.designtechnologies.com
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www.esi-group.com
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www.dynaform.com
37. Forming Technologies Inc., FastForm User Manual, Oakville, Ontario, Canada.
www.forming.com
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www.mastercam.com
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# APPENDIX A.  TESTBED PRESENTATION AND DEMONSTRATION MEETING

## A.1  Call for Meeting Sample E-mail

⚠ You forwarded this message on 11/16/2005 11:54 AM.
Attachments can contain viruses that may harm your computer. Attachments may not display correctly.

| | |
|---|---|
| **From:** Chang, Kuang-Hua | **Sent:** Wed 11/16/2005 11:35 AM |
| **To:** robert.ochs@tinker.af.mil; Don.Arrowood@tinker.af.mil | |
| **Cc:** | |
| **Subject:** Air Force Project Review and Demonstration | |
| **Attachments:** 🗋 AbstractKHCZ505.pdf(749KB) 🗋 Meeting Agenda.doc(113KB) | |

Dear Bob and Don,

Dr. Siddique and I have been working on a reverse and re-engineering project at OU, funded by Air Force Research Lab (AFRL), in the past three and half years. We have explored various software and equipment and established an integrated system that is capable of supporting general reverse and re-engineering tasks. Some of the examples, such as B-52 anti-icing tubing and E-3 torque tubes, we tested are from Tinker. The attached abstract should provide adequate details on the effort.

We believe the technology we put together in this project will be of your interest. Therefore, we would like to invite you to join our project review and demonstration meeting. The meeting will be held at:

AME Conference Room, Felgar Hall, 865 Asp Avenue, Norman, OU ,
1:30-3:30 PM, Wednesday, November 30.

The meeting agenda and map to Felgar Hall is attached for your reference. Please let us know if your will be able to attend the meeting. We will also invite people from various weapon systems, including B-52, E-3, B-1, and C-135 to join us. We'd like to request your help to forward this meeting notice to anyone in Tinker you think will be interested. Thank you.

Regards,

Kuang-Hua Chang, Ph.D.
Professor
Williams Companies Foundation Presidential Professor
School of Aerospace and Mechanical Engineering
The University of Oklahoma
Norman, OK 73019
(405) 325-1746 (O)
(405) 325-1088 (Fax)
E-mail: khchang@ou.edu

Done | 🔒 Unknown Zone (Mixed)

## A.2  Attendant List

| Name | Division | Phone Number | E-mail |
|---|---|---|---|
| Marin Meas | 327th CSSG/GFSYRA | (405) 736-3674 | marin.meas@tinker.af.mil |
| Bob Ochs | 448 MSUG/GBMTD | (405) 736-7454 | robert.ochs@tinker.af.mil |
| Don Arrowood | 448 MSUG/GBMTD | (405) 736-7454 | don.arrowood@tinker.af.mil |
| Don Koepp | 448 MSUG/GBMTD | (405) 736-7454 | don.koepp@tinker.af.mil |
| Ksirtian Olivero | 76 CMXG/MXCP | | kristian.olivero@tinker.af.mil |
| Jack Haley | Tec Masters | (580) 581-2585 | jhaley@tecmasters.com |
| Kuang-Hua Chang | OU | (405) 325-1746 | khchang@ou.edu |
| Zahed Siddique | OU | (405) 325-2692 | zsiddique@ou.edu |
| Mangesh Edke | OU | (405) 325-0162 | mangeshe@ou.edu |
| Zhiqiang Chen | OU | (405) 325-5011 | chzqiang@ou.edu |

## A.3 Meeting Agenda

**PROJECT REVIEW AND DEMONSTRATION MEETING**

**Reengineering and Fast Manufacturing For Impact-Induced Fatigue and Fracture Problems in Aging Aircrafts**

AFOSR GRANT F49620-02-1-0336

1:30-3:30 PM, Wednesday, November 30, 2005
AME Conference Room, Felgar Hall, 865 Asp Avenue, Norman, OU

| | |
|---|---|
| 1:30-1:40 | Welcome |
| 1:40-2:30 | Testbed Review |
| | Reverse Engineering Technology and Tool Set |
| | Re-Engineering and Fast Prototyping |
| | System Integration and Design Collaboration |
| 2:30-3:20 | Testbed Demonstrations |
| | Reverse Engineering of B-52 Anti-Icing Tubing |
| | Re-Engineering and Manufacturing of E-3 Torque Tube |
| 3:20-3:30 | Comments and Feedback |
| 3:30 | Adjourn |

## A.4 Sample Survey Forms Collected

# APPENDIX B. PUBLICATIONS

## B.1 MS Thesis (2)

1. Edke, M.S., Shape optimization for structural performance and manufacturing cost of heavy load carrying components, MS Thesis, The University of Oklahoma, May 2005.
2. Gibson, D.C., Parametric feature recognition and surface construction from digital point cloud scans of mechanical parts, MS Thesis, The University of Oklahoma, December 2004.

## B.2 Referred Journal and Book Chapters (6)

1. Chen, Z. and Siddique, Z., A system to support collaboration in a distributed environment for conceptual design, Accepted: International Journal of Agile Manufacturing.
2. Chen, Z. and Siddique, Z., 2004, COLCON: A system to support collaboration in a distributed environment for conceptual design, Submitted to: *ASME-JCISE* (Currently under revision).
3. Edke, M.S. and Chang, K.H., Shape Optimization of Heavy Load Carrying Components for Structural Performance and Manufacturing Cost, Journal of Multidisciplinary Structural Optimization, Accepted, July 2005.
4. Chang, K.H. and David, D., A Study on Parametric Solid Modeling for Air Logistics Support, ASME Journal of Computing and Information Science in Engineering, submitted, September 2005.
5. Chang, K.H., All-Digital Design and Manufacturing—A New Development in Engineering Education, 2006 iNEER Special Volume, Accepted, December 2005.
6. Chang, K.H., Siddique, Z., Edke, M., and Chen, Z., An Integrated Testbed for Reverse Engineering of Aging Systems and Components, Computer-Aided Design and Applications, Vol. 3, Nos. 1-4, 2006, Accepted.

## B.3 Referred Conference Proceedings and Presentations (12)

1. Chen, Z. and Siddique, Z., 2005, A cooperative-collaborative design system for concurrent mechanical design, ASME IDETC 2005 Conference, DETC2005-85005.
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5. Chen, Z. and Siddique, Z., 2003, Elements and techniques to develop a distributed design framework, Proceedings of DETC'03: 23RD ASME Computers and Information in Engineering Conference, September 2-5, 2003, Chicago, IL, Paper No. DETC2003/CIE-48229
6. Gibson, D.C. and Chang, K.H., Parametric Feature Recognition and Surface Construction from Digital Point Cloud Scans of Mechanical Parts, Proceedings of the International Conference on Computing, Communications and Control Technologies: CCCT'04, Austin, Texas, August 14~17, 2004.
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9.  Chang, K.H., All-Digital Design and Manufacturing—A New Development in Engineering Education, iCEER-2005 iNEER Conference for Engineering Education and Research, Tainan, Taiwan, March 1~5, 2005.
10. Chang, K.H. and Edke, M.S., Shape optimization of heavy load carrying components for structural performance and manufacturing cost, Sixth World Congress of Structural and Multidisciplinary Optimization (WCSMO-6), Rio de Janeiro, Brazil, 30 May ~ 3 June, 2005.
11. Edke, M.S. and Chang, K.H., Shape Optimization for Cost and Performance of Structural Components, CE2005, 2nd AIAA Multidisciplinary Design Optimization Specialist Conference, 1-4 May 2006, Newport, Rhode Island, accepted, August 2005.
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## B.5   Project Reports (5)

1.  Siddique, Z. and Chang, K.H., Reengineering And Fast Manufacturing For Impact-Induced Fatigue And Fracture Problems In Aging Aircrafts, Air Force Office of Scientific Research Contractor's Meeting in Mechanics of Materials and Devices & Structural Mechanics, Holiday Inn, Rosslyn at Key Bridge, Arlington, VA, September 25~27, 2002 (proceedings in CD-ROM).
2.  Chang, K.H., and Siddique, Z., Reengineering And Fast Manufacturing For Impact-Induced Fatigue And Fracture Problems In Aging Aircrafts, Air Force Office of Scientific Research Contractor's Meeting in Mechanics of Materials and Devices & Structural Mechanics, Eldorado Hotel, Santa Fe, NM, September 8~11, 2003 (proceedings in CD-ROM).
3.  Chang, K.H., and Siddique, Z., Reengineering And Fast Manufacturing For Impact-Induced Fatigue And Fracture Problems In Aging Aircrafts, Air Force Office of Scientific Research Contractor's Meeting in Mechanics of Materials and Devices & Structural Mechanics, Wintergreen Resort, Wintergreen, VA, August 16~20, 2004 (proceedings in CD-ROM).
4.  Chang, K.H., and Siddique, Z., Reengineering And Fast Manufacturing For Impact-Induced Fatigue And Fracture Problems In Aging Aircrafts, Air Force Office of Scientific Research Contractor's Meeting in Mechanics of Materials and Devices & Structural Mechanics, Eldorado Hotel, Santa Fe, NM, August 29~September 1, 2005 (proceedings in CD-ROM).
5.  Chang, K.H., and Siddique, Z., Reengineering And Fast Manufacturing For Impact-Induced Fatigue And Fracture Problems In Aging Aircrafts, Project Final Report, submitted, January 2006.

## B.6   Student Theses (2)

1.  Edke, M.S., Shape Optimization for Structural Performance and Manufacturing Cost of Heavy Load carrying components, MS. Thesis, the University of Oklahoma, May 2005.
2.  Gibson, D.C., Parametric Feature Recognition and Surface Construction From Digital Point Cloud Scans Of Mechanical Parts, MS. Thesis, the University of Oklahoma, December 2004.

# APPENDIX C. LIST OF MODEL FILES AND DOCUMENTS INCLUDED IN CD

| Folder | File Name | File Type | Contents |
|---|---|---|---|
| Presentation Files | Tinker Demo.ppt | Power Point | Project review and introduction to RE Testbed |
| Demonstration Documents | 2.2 Workflow template for B-52 Tubing Project.doc | Word | B-52 Tubing project workflow |
| | 2.3 Product Description.doc | Word | Description of B-52 Tubing part |
| | 2.4 Solution Conference Summery.doc | Word | A summery of |
| | 2.5 Point Cloud Raw Data.doc | Word | Image of Tubing point cloud |
| | 2.6 Extracted Solid Process 4.doc | Word | Introduction to extracted geometry solid modeling |
| | 2.7 Feature Profile Image.doc | Word | Image of feature profile model |
| | 2.8 Main Branch Model.doc | Word | Image of main branch model |
| | 2.9 Final Solid Model.doc | Word | Image of Tubing solid model |
| | 2.10 Error Measurement Image.doc | Word | Error measurement image |
| | 3.2 Workflow template for Torque Tube project.doc | Word | Torque Tube project workflow |
| | 3.3 Torque Tube Problem Description.doc | Word | Torque Tube problem description |
| | 3.4 Summary of Material and Design Conference.doc | Word | Summery of material selection and design solution |
| | 3.5 Torque tube CAD model.doc | Word | Image of Torque Tube model |
| | 3.6 Torque tube FEA model.doc | Word | Image of Torque Tube FEA model |
| | 3.7 Torque tube VM model.doc | Word | Image of Torque Tube Virtual Machining model |
| | 3.8 Virtual Machining Report for the Torque Tube.doc | Word | Virtual Machining report |
| | 3.9 FEA and GSA Report for the Torque Tube.doc | Word | FEA and Global Sensitivity Analysis report |
| Technical Papers | colcon.pdf | PDF | A system to support collaboration in a distributed environment for conceptual design |
| | colcon.pdf | PDF | COLCON: A system to support collaboration in a distributed environment for conceptual design |
| | Struct Multidisc Optim-Paper-MSE KHC-0503.doc | Word | Shape optimization of heavy load carrying components for structural performance and manufacturing cost |
| | A Study on Parametric Solid Modeling for ALS.doc | Word | A Study on Parametric Solid Modeling for Air Logistics Support (in review) |
| | iNEER.doc | Word | All-digital design and manufacturing a new development in engineering education |
| | DETC2005-85005.pdf | PDF | A Cooperative-collaborative |

| | | | Design System for Multidisciplinary Mechanical Design |
|---|---|---|---|
| | collaboration_template_ce3_formated.doc | Word | A Cooperative/collaborative Design System for Concurrent Multidisciplinary Mechanical Design |
| | IMECE2004-61318.pdf | PDF | Web-based Mechanical Engineering Design Education Environment Simulating Design Firms |
| | IMECE2003_42781.doc | Word | CORBA-based task requirement driven design system |
| | DETC2003-48229.doc | Word | Elements and techniques to develop a distributed design framework |
| | Gibson DC and Chang KH - CCCT 2004 Conference.pdf | PDF | Parametric Feature Recognition and Surface Construction from Digital Point Cloud Scans of Mechanical Parts |
| | Edke MS and Chang KH - CCCT 2004 Conference.pdf | PDF | Concurrent Shape Optimization of Structural Components |
| | OSU_Symposium_Presentation.ppt | PDF | Concurrent Shape Optimization of Structural Components |
| | Chang KH - iNEER Conference Paper.pdf | PDF | All-Digital Design and Manufacturing—A New Development in Engineering Education |
| | Chang KH and Edke MS - WCSMO-6 Conference.pdf | | Shape optimization of heavy load carrying components for structural performance and manufacturing cost |
| | Edke MS and Chang KH - AIAA 2006 Conference | | Shape Optimization for Cost and Performance of Structural Components |
| | Chang Siddique Edke Chen - CAD06 Conference.pdf | PDF | An Integrated Testbed for Reverse Engineering of Aging Systems and Components |
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